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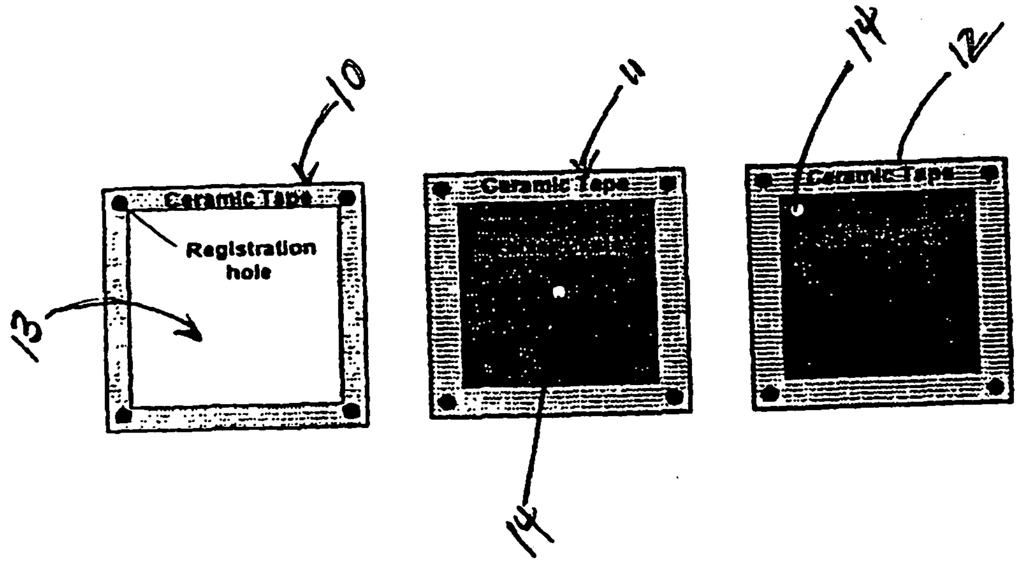
(54) Title: MINUTE ELECTROMECHANICAL ACTUATION AND FLUID CONTROL DEVICES AND INTEGRATED SYSTEMS BASED ON LOW TEMPERATURE CO-FIRED CERAMIC (LTCC) TAPE TECHNOLOGY



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(57) Abstract: Disclosed are minute electromechanical devices (10, 11, 12), as electromagnetic actuators, pressure transducers, pumps and valves, which are conveniently fabricated from ceramic tape to yield monolithic ceramic and hybrid structures.

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MINUTE ELECTROMECHANICAL ACTUATION AND FLUID CONTROL DEVICES AND INTEGRATED SYSTEMS BASED ON LOW TEMPERATURE CO-FIRED CERAMIC (LTCC) TAPE TECHNOLOGY

Cross-Reference to Related Application

This application claims the benefit of U.S. Provisional Patent Application No. 60/165,180, filed November 12, 1999, the entire disclosure of which is incorporated by reference in the present application as though set forth herein in full.

Field of the Invention

This invention relates to minute electro-mechanical devices, such as electromagnetic actuators, pressure transducers, pumps, relays, valves, and peristaltic pumps and stirrers that are readily fabricated from ceramic tape alone and ceramic tapes in conjunction with non-ceramic materials, such as Kapton™ or the like. The present invention also includes a meso-scale electro-mechanical system that may include one or all of the devices described herein.

Background of the Invention

Silicon technology has made possible the batch manufacturing of highly precise, dense, relatively large scale integrated circuits.

Attempts have been made in the manufacture of meso-scale electro-mechanical devices and systems to exploit silicon as a high precision, high strength, high reliability mechanical material that facilitates the production of components and devices which integrate sensors, mechanical elements and electronic circuits. Experience has shown, however, that the proposed fabrication techniques involve many of the same

disadvantages encountered in the manufacture of silicon-based integrated circuit modules. In general, the fabrication of silicon-based, meso-scale devices and systems requires specialized equipment and highly trained personnel, resulting in substantial capital investment and manufacturing costs. Apart from the relatively high cost, it is difficult to package and interface meso-scale electromechanical devices with one another and to fabricate relatively large, three-dimensional meso-scale structures, particularly those having fluid handling elements.

Other materials of fabrication for meso-scale electromechanical devices and systems, such as glass and plastic, have similar drawbacks with respect to the difficulty and cost of manufacture of three-dimensional structures.

Accordingly, a need exists for meso-scale electromechanical devices of the type mentioned above, which can be readily integrated into three-dimensional structures and which can be easily and economically manufactured.

Summary of the Invention

The present invention provides minute mechanical, fluid control and electronic devices and integrated systems that are assembled from or utilize structures which are fabricated from ceramic tape, or hybrid structures made of both ceramic tapes and other structural materials, and which may incorporate one or more of the following: actuators, switches, sensors, pressure transducers, thermistors, valves, pumps, stirrers and hydraulic interconnects. All of these devices are fabricated using a technique that allows machining of flow conduits into individual

layers and/or printing of conductors and resistors upon one or more of these layers.

Ceramic tape affords a convenient and versatile medium for the custom fabrication of meso-scale mechanical and fluidic devices ranging in characteristic sizes from a few microns to a few millimeters, and for the integration of electrical conductors and resistors into a single monolithic device. These elements can be assembled as individual devices and interfaced externally or installed readily in a three dimensional structure.

Ceramic tapes have a distinct advantage over silicon and glass in that minute structures, with minimum features in the size range from 10 microns to several thousand microns are easily fabricated. This is feasible because in the pre-fired (green) state, ceramic tapes are soft, pliable, and easily dissolved and abraded. Individual layers can be machined separately, stacked, aligned, and co-fired. Once a layered ceramic tape structure is fired, it becomes a tough and highly rigid body. Many layers of ceramic tapes, up to about 80 layers, can be bonded together to form complex three-dimensional structures. Electrically conducting paths can be built into these structures, and the incorporation of different materials into these substrates can be easily achieved.

Ceramic tape thus provides a convenient, and flexible medium for the fabrication and encapsulation of the various components described above for a variety of applications.

In addition to their versatility in fabrication and design, ceramic tapes offer many desired physical properties. Ceramic tapes can bond at relatively low temperatures, yet offer

a relatively high thermal conductivity, comparable to that of glass. Green tape devices can withstand higher usage temperatures than comparable devices made from other media. Green ceramic tapes can be more easily connected to a sample introduction device than analogous materials. Also, sub-components such as optics, silicon or metal windows, can also be conveniently integrated into channels or layers within the ceramic tape structure.

According to one aspect, the present invention provides a ceramic tape-based device that comprises metallic and polymer materials and incorporates active, moving structural elements that function as electromagnetic actuators. Electromagnetic force is used for activation. In recent years, electromagnetic actuators have gained popularity over electrostatically driven actuators for micro and meso-scale applications. A electromagnetic field can be induced by passing current through electromagnetic coils made out of conductor paste and fabricated onto individual layers of ceramic, green-state tapes. Structures which comprise one or more layers of ceramic tape containing such coils can be made which gather, focus, and then harness electromagnetic forces to create motion.

The electromagnetic actuation device of the invention comprises a flexible member which is adapted to be supported by one part thereof and to be deflected at a second part upon actuation, with multiple ceramic layers constituting the body of the device. A first ceramic layer supports the one part of the flexible member. A second ceramic layer comprises at least one electromagnetic coil and at least one contact member for

effecting current flow through the coil. The coil of the second layer is positioned adjacent the flexible member. At least the second part of the flexible member has magnetic properties so as to be deflected upon current flow through the coil. The actuation device may optionally include at least one other ceramic layer comprising at least one electromagnetic coil and at least one contact member to effect current flow through each electromagnetic coil of the other ceramic layer(s). It is preferred that the coil of any other ceramic layer(s) be substantially coextensive with the coil of the second layer. The contact members are operable to activate the device by the flow of current through the electromagnetic coils, thereby effecting actuation of the flexible member.

The ceramic tape-based electromagnetic actuators described herein are capable of producing magnetic fields up to tens of Gauss, and motions up to a few millimeters. Coils on different layers can be interconnected by conductor-paste filled vias or channels. Such actuators can be used for switches, valves, motors, stirrers and pumps in a meso-scale mechanical and fluidic components system or chip.

According to another aspect, the present invention provides transducers and sensors fabricated of ceramic tape. These devices respond to a physical stimulus such as temperature, light, sound, pressure, motion, humidity, flow, or the like and produce a corresponding electrical signal. For example, one embodiment of the present invention is a meso-scale pressure transducer fabricated from ceramic tapes. Pressure transducers can be utilized in a wide variety of applications and industries

such as industrial instrumentation, pumps, compressors, pressure control systems, and automotive control systems. The pressure transducers of the present invention are in the meso-scale range, and can be fabricated as small as 8μm in diameter with an internal cavity of 2μm. Because they are based on a ceramic tape substrate, they are capable of being subjected to higher pressure and temperatures relative to analogous silicon devices known in the art. For example, a pressure transducer fabricated from ceramic tape will have enhanced properties for operations above 150°C.

All parts for the transducer can be machined from green ceramic tapes utilizing either a computer numerically controlled (CNC) milling machine, or an isotropic etching technique involving the removal of the glassy binder of a partially sintered tape. This chemical exfoliation technique may be employed to separate the green ceramic tape into three layers, the middle layer being highly elastic, isotropic and homogeneous. The middle layer is then chemically thinned to achieve membrane like characteristics, with a thickness as small as about 50μm.

According to yet another aspect, the present invention provides an electromagnetically actuated, hybrid, meso-scale valve based on ceramic tape technology. These devices offer the advantage of shorter response time, lower power consumption, lower inactive volume and good dynamic characteristics. Analogous silicon micro-machined valves, by comparison, suffer from clogging or blockage due to moving parts within the micro valves.

The meso-scale valve of the invention has a body member which comprises at least first and second ceramic layers that define a flow channel, with an inlet port and an outlet port for transporting fluid through said flow channel, and a valve opening positioned in the flow channel between the inlet port and outlet port. The valve also includes a flexible diaphragm member which has a flexed condition engaging the valve opening and an unflexed condition disengaging the valve opening. Engagement of the valve opening by the flexible diaphragm member interrupts fluid transport through the flow channel. The valve further includes a base member comprising at least one other ceramic layer having at least one electromagnetic coil and a magnet mounted on the flexible diaphragm member to provide a magnetic force that causes the diaphragm to assume the flexed condition upon current flow through the electromagnetic coil.

According to still another aspect, the present invention provides meso-scale, electromagnetic, reciprocating diaphragm pumps fabricated from ceramic tapes and polymer films. The meso-scale pump of the invention has an inlet, an outlet, a pump cavity with first and second check valves, which control the opening of the inlet and outlet, respectively, and at least one flexible diaphragm adapted to be reciprocated to deflect into the cavity. The pump cavity is formed in a first ceramic layer, with at least one flexible diaphragm member being supported on the first ceramic layer overlying the cavity, and comprising at least one electromagnetic coil. A magnet is positioned in relation to the at least one flexible diaphragm member to provide a magnetic force effecting reciprocation of such member(s) upon current flow

through the coil. The valves operate to permit fluid flow through the cavity upon reciprocation of the flexible member(s).

In one pump design, a chamber, which is machined in ceramic tape substrate layers, is covered on one side with a polymer film diaphragm on which copper coils are formed. The diaphragm is electromagnetically actuated by the magnetic field of a permanent magnet. Flap valves, also made of polymer film, serve to control fluid flow into and out of the chamber. In another design, the chamber is covered on both sides with polymer film diaphragms, with coils formed on both diaphragms. Current is caused to be transmitted through these coils in opposite directions, also by the magnetic field of a permanent magnet.

Brief Description of the Drawings

The foregoing summary, as well as the following detailed description of the preferred embodiments, is better understood when read in conjunction with the appended drawings, in which:

Figure 1a is an isometric view of individual layers of ceramic tape prior to stacking, lamination and sintering.

Figure 1b is a cross-sectional view of the assembled and post-fired ceramic tape structure taken at line A-A depicted in Figure 1a.

Figure 2a is a plan view of three layers of green or unfired ceramic tape that together comprise a ceramic tape electromagnetic actuator.

Figure 2b is a plan view of the three layers of green or unfired ceramic tape which illustrate the electromagnetic

coils within the ceramic tape electromagnetic actuator of Figure 2a.

Figure 3a is a cross-sectional view of a ceramic-tape based actuator which includes a Kapton beam.

Figure 3b is a cross-sectional view of the experimental setup of a permanent magnet actuator which includes a Kapton beam.

Figure 3c shows the tip deflection of the Kapton cantilever beam as a function of coil current.

Figure 4a is a cross-sectional view of a ceramic-tape based actuator which includes a permalloy beam.

Figure 4b is a cross-sectional view of the experimental setup of a permanent magnet actuator which includes a permalloy beam.

Figure 4c shows the tip deflection of the permalloy cantilever beam as a function of coil current.

Figure 4d is an exploded, perspective view of the actuator device of Figure 4a, further including an underlying permalloy layer.

Figure 5 shows the exfoliation process for a partially sintered ceramic tape layer.

Figure 6a is a plan view of a ceramic tape-based pressure transducer.

Figure 6b is a cross-sectional view of the pressure transducer of Figure 6a.

Figure 7 shows the response of the ceramic tape transducer over time in comparison to the response of a silicon transducer.

Figure 8 is a cross-sectional view of a hybrid meso-scale valve.

Figure 9 depicts the various steps of the fabrication process for the flexible diaphragm of the valve of Figure 8.

Figure 10 is a plan view of the actuating coil geometry and a cross-sectional view of the layer interconnection for a five layer valve device.

Figure 11 is an exploded perspective view of a one diaphragm, meso-scale electromagnetic pump, in accordance with the present invention.

Figure 12 is an exploded perspective view of a two diaphragm, meso-scale electromagnetic pump, in accordance with the present invention.

Figure 13a is a plan view of two machined layers of LTCC tape and a polymer film diagram that together comprise a meso-scale electromagnetic reciprocating diaphragm pump in accordance with the present invention. The diaphragm layer is shown with and without check valves associated with the inlet and outlet ports in the ceramic tape layer.

Figure 13b is a cross-sectional view of the three layers of Figure 13a, laminated and co-fired in a monolithic three-dimensional structure, including passive valves.

Figure 14 illustrates the step-wise fabrication of the diaphragm component of the electromagnetic reciprocating diaphragm pump shown in Figures 13a and b.

Figure 15 is a graphical representation of the air-pumping flow rate (mL/min), as a function of actuation frequency (Hz) for the pump design shown in Figure 11.

Figures 16a and b provide a schematic illustration of the operation of the pump of Figure 11, with electromagnetically controlled valves.

Figure 17 shows the inclusion of a soft magnetic material in a cavity of a meso-scale structure built up from layers of co-fired ceramic tapes.

Detailed Description of Preferred Embodiments

Green ceramic tape is a versatile material that enables the combination of various electronic and meso-scale mechanical and fluid control elements into an integrated system within a monolithic structure, without the need for using external hydraulic interconnections. The term "minute" as used herein in reference to channels, passageways, conduits, vias, interconnections, cavities, chambers or other void spaces of the devices described below, is intended to signify at least one cross-section dimension of width or depth on the order of 10μm to 1cm, preferably on the order of 20μm to 500μm, and more preferably 50μm to 300μm. For many applications, channels of 200μm width will be useful. Cavities in the structures may have somewhat larger dimensions (e.g. 60μm to 1cm). The term "minute" and "meso-scale" are sometimes used interchangeably herein.

In fabricating the devices of the invention, ceramic tape layers are sized to meet the external dimensions of the intended device with the tape in its green or unfired state. Next, minute flow conduits, channels and/or portals are formed in the individual layers of tape. These flow conduits, channels or portals can be created in a variety of ways that include, but

are not limited to, mechanical machining (e.g., CNC milling and punching), chemical etching, laser machining, binder extraction, photo-forming or related techniques known in the art. A variety of shapes of flow conduits, including without limitation straight, T-shaped, U-shaped, L-shaped, spirals or curves, can be incorporated into one or more of these layers. Flow conduits in various layers are interconnected through the use of hollow vias. Alternatively, or in addition to the flow conduits, the layers may be printed with a pattern of metallic paths, conductors, thermistors, electrodes, electrical contacts, resistors, dielectric, or other electron conducting media, and co-fired. These layers are aligned, stacked, and then laminated together by sintering under tempertaure and pressure conditions sufficient to yeild a hardened, monolithic body, with complex internal interconnections. As another alternative, the aforementioned electronic components can be vapor deposited onto post-fired tapes. Tape composition may vary from layer to layer depending upon the desired properties and applications of a particular device or system.

One of the difficulties encountered in applying ceramic tape technology is the occurrence of dimensional changes, such as shrinkage, bowing and other related deformations, that occur during the lamination and sintering process. Deformation usually occurs in the direction perpendicular to the tape's x-y plane and the degree of shrinkage can be up to 15% of the tape's original dimensions. The degree of shrinkage on the external dimensions can be corrected by accounting for the shrinkage in the design process. It is more difficult, however, to correct the

dimensional changes such as shrinkage and bowing for the internal cavities or flow conduits. To remedy this, the internal cavities or flow conduits of the device are filled with sacrificial material, such as graphite and an organic binder mixture, prior to the lamination and sintering process. The sacrificial material then burns out during the sintering process and a hardened, monolithic device with a reduced amount of shrinkage on the internal conduits or cavities is produced.

In the fired state, small structures can be subsequently machined using diamond tools and lasers. Diamond points are used to create intricate features with small dimensions, and diamond slurry can be used to define symmetrical shapes. Both CO_2 and eximer lasers may be utilized to machine alumina and other ceramics with high precision.

Interconnects to an external flow supply can be added to the ceramic device through applying an adhesive, such as epoxy, to affix glass or metal fittings to the surface of the ceramic. If desired, glass fittings such as Kimble's Borosilicate Glass (KIMAX Brand N-51A) can be directly bonded to the ceramic by heating the glass above its transition temperature because the thermal expansion coefficient closely matches that of ceramic tape. Furthermore, metallic fittings can be bonded by metallizing the surface of the ceramic device and brazing the fittings to the ceramic surface.

The devices disclosed herein and the flow conduits within them are adaptable to a variety of design requirements depending upon the application. Design adaptions will include, for example, the formation of conduits of various shapes,

insertion of electrodes, resistors, thermistors and conductors, surface modifications, and the like. An example of a surface modification may be the application of an impervious coating to the internal cavities to reduce surface roughness and ease the passage of fluid through these cavities.

Because of their versatility, the devices of the present invention can be readily adapted to create meso-scale devices or systems that may include, but are not limited to, the following: electromagnetic actuators; reaction chambers; flow rate sensors; valves; integrated heat exchangers; flow conduits; thermistors; pumps, such as electromagnetic pumps or peristaltic pumps, stirrers, or heat pipes. The flexibility of the manufacturing method allows devices of other materials such as silicon or metal windows to be incorporated or embedded into the ceramic structure.

In preferred embodiments, the individual layers of the meso-scale devices comprise DuPont® 951 series Green Tape™. This tape is a low temperature co-fire ceramic ("LTCC") tape which consists primarily of alumina particles, glass frit, and organic binder. The tape is characterized by high strength, low coefficient of thermal expansion, refire stability, and is compatible with co-fired conductors (such as conducting paste that is screen-printed to the green ceramic tape) and via fill compositions. The thickness of the tape used for the devices can vary anywhere from about 100μm to about 250μm. As those skilled in the art will appreciate, however, other ceramic tapes can be utilized in practicing this invention.

The shrinkage of DuPont® g51 Green Tape™ is on the order of 12.27%±0.3% in the x, y direction and 15%±0.5% in the z direction, according to the DuPont® Design Parameters and Considerations for Green Tape™, which are incorporated herein by reference. Shrinkage can be affected further by the number and size of cavities within the individual layers or the degree of metallization on each layer.

Figure 1a depicts 3 layers of green ceramic tape designated 1, 2, and 3. Layer 3 has two openings, 4 and 5, that are formed by CNC milling or punching. Layer 2 has an L-shaped conduit or flow channel 6 therein. Holes 4 and 5 and flow channel 6 are formed by placing layer 1 and layer 2, respectively, onto the platform of a CNC milling machine. The green layers are held in place by a vacuum chuck or similar means. The CNC milling machine cuts openings 4 and 5 or flow channel 6 in accordance with a computer generated design for each individual layer of the device. Openings 4 and 5 and flow channel 6 are filled with a mixture of graphite and organic binder to maintain dimensional integrity of these internal cavities during the lamination and sintering steps. The graphite and organic binder mixture burns out during the sintering process.

Lamination and sintering can occur in a variety of ways and at different time, temperature, and pressure settings depending upon the ceramic tape used for the device, the number of layers, and any devices or pastes that are applied to the individual layers pre-firing. The aligned and stacked layers are subjected to temperature and pressure parameters sufficient to

bond the layers together into a unitary structure. Uniaxial lamination takes place in a hydraulic press with heated platens. The aligned, layer stack is pressed at about 70°C and 3000 psi for about 10 minutes to form a laminate. DuPont, the manufacturer of the 951 series tape, recommends that the laminate be typically rotated 180° after the first five (5) minutes. Alternatively, isostatic lamination occurs in a specially designed press which uses heated water or other fluid. Time and temperature are usually the same as uniaxial pressing but rotation of the laminate is not required. The laminate is vacuum sealed within a plastic bag to prevent water from attacking the ceramic tape layers.

After lamination is complete, the laminate is then fired on a setter tile within a kiln or furnace. The graphite and organic mixture and other organics within the laminate burnout at temperatures which range from about 200°C to about 500°C. The laminate is usually "soaked" within this temperature range to ensure full decomposition of the organics. The temperature is then gradually increased to the sintering temperature. Typical sintering temperatures for ceramic tape devices are between about 850°C to about 875°C. The device may be further subjected to additional firing steps if thick film resistors, dielectric, conductors, or other devices are applied in a post-fire operation.

Layers 1, 2, and 3 are aligned and stacked together to form a monolithic structure or device, 7 as shown in Figure 1b. Each layer is placed into a precision lamination fixture and positioned over tooling pins until all layers of the device 7 are

assembled. Figure 1b is a cross-sectional view of the ceramic tape structure after stacking, lamination and sintering taken at line A-A depicted in Figure 1a. Opening 4 can be used as an inlet port of the device 7 and flow channel 6 can be used as a capillary or fluid sample holder depending upon the desired application of device 7. Fittings can be affixed to opening 4 to facilitate introduction of fluid into flow channel 6. Opening 5 (not shown in Figure 1b) can be used as an outlet port of device 7 and can also have a fitting attached to it to facilitate fluid removal from the device.

The device 7 may be subjected to post-firing machining depending upon the desired application and design parameters. Machining methods vary depending upon considerations of cost, edge control, tolerances, and shape. A dicing saw may be used to form rectangular sharped devices with tight outside dimensional tolerances and high quality edges. Another machining method, ultrasonic cutting, allows tight tolerances and exceptional edge quality of unusually shaped parts. The drawback to ultrasonic cutting is that it is expensive and slow in comparison with other cutting methods. Yet another machining method, laser cutting, allows for tight tolerances at a lower price than comparable methods. However, the quality of the edges produced by laser cutting is poor. In comparison with post-firing laser cutting, pre-firing laser cutting of green ceramic tape will produce quality edges. Unfortunately, the outside edge tolerances of pre-fired laser machine parts are poor due to dimensional changes resulting from firing.

As previously noted, hybrid devices can be fashioned from LTCC tapes in conjunction with various other structural materials. Hybrid structures for high temperature applications may incorporate glass compositions, silicon or metals, so long as the thermal expansion coefficient of the selected material is compatible with the ceramic material. Once the ceramic is fired, a wide variety of plastic materials may be included in the resulting monolithic structure. Exfoliated, partially sintered LTCC tape may be used as a diaphragm material in the various devices described herein.

The fabrication methods described herein enable rapid prototyping, layered manufacturing with its attendant advantages and economical production of various minute, mechanical, fluid control and electronic devices and systems.

The following examples are provided to describe the invention in further detail. These examples are provided for illustrative purposes only, and should in no way be construed as limiting the invention.

EXAMPLE I: ELECTROMAGNETIC ACTUATORS

Figure 2a depicts the three major fabrication steps of electromagnetic actuators made using ceramic tape in accordance with this invention. Three layers of stamped-out 275mm thick DuPont 951 ceramic tapes with registration holes were used in the actuators of the current example. The top layer 10 supports the beam in space. The middle 11 and bottom 12 layers are substrates for the electromagnetic coils. The coils can be either screen-printed in the required pattern or CNC milled to a desired

pattern after depositing a layer of the conducting paste on the entire surface of the tape. In the present example, a CNC machine was used to cut a large square open space 13 in the top layer 10 and vias or small openings 14 on layers 11 and 12.

Figure 2b is a top view which illustrates the coil structure of a 3 layer actuation device. Silver Du Pont 6142D conductive paste was deposited on top of the bottom two layers 11 and 12. Vias 14 were also filled with silver Du Pont 6141 conductor paste. Coils 15 were milled by a CNC milling machine. An end-milling cutter with a 125μm radius was used to pattern each layer of the ceramic tape as needed. To allow connection with a power source, contact pads 16 composed of Du Pont 6146 conductor paste were printed on the coil ends. Electrical wires from the power source were soldered directly onto these contact pads. The conductor line thickness and the spacing between the lines were both 200μm after firing. The coil depicted in Figure 2b has 7 windings. The electrical resistance of the two-layered coils was 1.2Ω. The force experienced by the magnet in the vertical direction due to the magnetic field is determined by

$$F_z = M_z \int_V \frac{\partial B_z}{\partial z} dV, \qquad (1)$$

where F_z is the electromagnetic force in the vertical direction, M_z is the magnetization of the magnet, B_z is the z-component of the magnetic field due to the coils, and V is the volume of the magnet. B_z ($=\mu_o H_z$) induced by a single rectangular current loop

can be found in Wagner, B., Benecke, W., "Microfabricated Actuator With Moving Permanent Magnet," in *Proc. 1991 IEEE MEMS Conf.*, Nara, Japan, pp. 27-32, which is incorporated herein by reference. B_z induced by multiple loops can be found by adding B_z induced by each loop. In the above, it is assumed that B_z is not affected by the presence of the magnet.

After individual layers 10, 11, and 12 were machined, the three layers were aligned, laminated, and fired. A beam was bonded to the top layer. For a cantilever beam subjected to tip load, P, the tip deflection of the beam, w, is

$$w = \frac{PL^3}{3EI}, \qquad (2)$$

where L is the length of the beam, E is the Young's modulus of the beam material, and I is the moment of inertia. The electromagnetic force due to coil current ranging is influenced by the beam stiffness and magnet's weight.

In one actuator design depicted in Figure 3a, a flexible material such as Kapton™, which is a polyimide film, is used as the deflecting or cantilever beam 21. However, other material selections which are deformable in response to an electromagnetic force may also be used if desired. Kapton™ is preferred because it exhibits good mechanical, electrical, and thermal properties and is capable of withstanding temperatures up to about 400°C. The Young's modulus of Kapton™ was 2.5 gega-pascal ("GPa"). The thickness of the Kapton™ sheet used for the actuator can range from about 7.5μm to about 125μm. In the embodiment in Figure 3a, the Kapton™ beam used for the actuator

was 13mm long, 5mm wide, and 50mm thick. The Kapton™ and fired ceramic tape were laminated to form a monolithic device 20 by coating FEP (fluoropolymer resin) on the Kapton™. An Edmund Scientific NdFeB permanent magnet 22 with a 3.2mm diameter and 1.5mm thickness was bonded to the tip of the Kapton™ beam. Magnet 22 has a 1.2T magnetization and a 0.091 gram mass. As Figure 3a further illustrates, the two-layered square coils each of which are planar spirals with seven turns actuated the magnet. The present invention is not limited to the configuration depicted. It is anticipated that fabrication of larger number of coil turns in a small area would allow for larger beam deflection.

Figure 3b shows the experimental setup used to find the deflection of the tip of the Kapton™ beam due to electromagnetic actuation. A small amount of silver paste 23 was printed at the end of the Kapton™ beam 21 and a thin wire 24 of negligible weight and stiffness was connected to allow electrical connection with a multimeter 25. A probe station 26 was fixed on top of a Z-stage 27 that could traverse with 5μm precision. When the probe 26 made contact with the end of beam 21, an electric circuit closed, and the multimeter measured a finite resistance. The deflection of beam 21 relative to its initial undeflected state was found by comparing the location where beam 21 was first contacted to where it was first "lost". To measure the height of the beam's tip, probe 26 was slowly lowered until the circuit closed and millimeter 25 measured a signal. Subsequently, the probe 26 was elevated until the signal was lost and the circuit opened. The beam's deflection was determined as the probe's

position when loss of signal occurred. Typically, up to 100mm elevation difference was observed between the points of contact and loss of contact. This hysterisis phenomenon is partially attributed to electric contact resistance and partially due to the probe applying force on the beam when lowered.

The current to the electromagnetic coil was gradually increased in 0.2 A increments up to 1.4A. The measurement of the deflection of the beam tip was repeated at each current level. The whole experiment was repeated six times to find the scatter in the measurements. The results of these experiments are reflected in Figure 3c. As an additional measure of verification, a ruler was positioned behind magnet 22 and the deflection measurements were video taped. Figure 3c shows the results of both the probe measurements (shown as circles) and the video measurements (shown as 'x's'). As Figure 3c illustrates, a beam deflection exceeding one millimeter was obtained when the current was 200mA.

An alternative embodiment of the actuator of the present invention is depicted in Figure 4a. In Figure 4a, a permalloy or soft magnetic material beam 31, rather than a magnet-supporting Kapton™ beam was used for deflection. The permalloy selected, which was manufactured by Hamilton Precision Metals, Inc., had a saturation magnetization of about 0.78T and Young's modulus of about 230GPa. The composition of permalloy beam 31 was 80.21% Ni, 14.474% Fe, 4.33% Mo, 0.47% Mn, 0.31% Si, 0.20%C, 0.003% P, and 0.003%S. The dimensions of the permalloy beam used in the present example was 17mm long, 2.3mm wide, and

25μm thick. The permalloy enhances the intensity of the magnetic field generated.

Figure 4b shows the experimental setup used to test the permalloy beam actuator. The experimental setup is similar to that depicted in Figure 3b with the Kapton™ beam actuator. In the absence of an electromagnetic force, the gap between the beam's tip and the top coil was 1mm. The same coil design, namely a seven winding square coil configuration on two ceramic tape layers, was also used here. However, an additional permalloy sheet 33 was bonded to the bottom of actuator 30. This permalloy layer helped intensify the magnetic field generated by the coils.

Contact was made with the beam in the absence of magnetic forces. A certain amount of current was then applied to the coil. The resulting magnetic field caused beam 31 to deform. As a result of the deformation, the probe circuit was rendered open. The Z-stage 27 was slowly lowered until contact with the beam 31 was re-established. Due to contact resistance between the probe 26 and the beam 31, the probe had to be lowered beyond the equilibrium beam deflection state. The probe 26 was then elevated until the probe circuit became open. The location where the probe circuit was rendered open was the deflection of the beam end relative to the undeflected state. Coil current was then increased and deflection was measured using the same technique. The current was varied from 0A to 0.8A. The whole experiment was repeated four times to find the scatter of the measurements.

Figure 4c provides the results of this experiment which reflects the tip deflection of the permalloy beam 31 as a function of coil current. A comparison of the tip deflection of the permalloy beam 31 was made with and without the additional permalloy sheet 33 bonded to the base of the actuator. For example, the permalloy beam 31 with the permalloy sheet 33 bonded to the base of the actuator 30 deflected about 0.5mm at a current of 0.4A. In absence of the additional permalloy sheet 33, the beam tip deflected only about 0.2mm. The addition of permalloy sheet 33 decreases the repulsion of the permanent magnet 22 attached to the beam. The presence of the permalloy layer 33, therefore, enhances attraction and reduces repulsion. It is evident that the presence of a permalloy sheet layer 33 significantly increases the deflection of the beam. A permalloy sheet layer 33 can easily be added to the ceramic tape laminate in the fabrication process to obtain even larger deflections.

Alternative embodiments can have a flexible membrane that is attached on both ends rather than one end. These devices can be either one way or two way actuation devices or switches. Further embodiments of actuation devices can have a flexible membrane or beam above a cavity within the center of the magnetic coils, as illustrated in Figure 4d. The actuation device of Figure 4d is composed of three (3) ceramic layers 110, 11 and 112, with a Kapton beam 121 supported by the top layer 110. Vias 114 provide electrical connection between the electromagnetic coils 115. A permalloy base layer 117 serves to intensify the magnetic field produced by the device. This device can be

integrated with or incorporated into a monolithic package further comprising a pump and/or one or more valves as exemplified below.

EXAMPLE II: PRESSURE TRANSDUCERS OR SENSORS

Additional embodiments of the present invention include ceramic tape based pressure transducers. A pressure transducer is essentially a bridge circuit with two sides. The output produced by a transducer is voltage. One side of the circuit contains a resistor that acts as a reference. The other side of the transducer contains a resister which acts as a sensing element.

These devices are generally made in accordance with the aforementioned method. However, ceramic layers which function as the membranes of these devices can be prepared by chemical exfoliation, etching or other means, to a thickness of about 50μm to about 150μm, more preferably about 50 to about 100μm. As a result of chemical thinning, these layers become highly elastic, isotropic and homogenous. Exfoliated membranes from either sintered or partially sintered LTCC tapes facilitate the fabrication of ceramic pressure transducers operable in the temperature range up to at least 150°C and pressures in the range from atmospheric to one milli-Pascal.

The manufacturing process of a green ceramic tape, such as the DuPont 951 series ceramic tape, forces the ceramic tape to form anisotropic layers on its top and bottom. The middle or center layer of the green tape is more isotropic than the top and bottom surfaces. The middle layer of the green tape which is either partially or fully sintered can be isolated by

various chemical processes. Figure 5 shows the separation of an individual ceramic layers by the exfoliation process. The exfoliation process seems to obey Fick's Law for both partially sintered and sintered samples. That is, the reaction that occurs in the exfoliation process is diffusion controlled. In the case of a steady state reaction the diffusion length, L, that molecule of the exfoliating agent travels before interacting with the substrate is given by:

$$L = \sqrt{D\tau}$$

Figure 5 depicts the stages of exfoliation process at 85°C of a partially sintered tape. The layers of partially sintered samples actually peel away. Chemical exfoliation of sintered ceramic tape layers is not as effective as with partially sintered tape. If a sintered tape is used, the outer layers brush or chip away rather than peel. Preferably, hydrofluoric ("HF") acid, which is commonly used to etch silica, is used as the exfoliating agent to separate the layers.

In a preferred embodiment, a partially sintered individual layer of series 951 ceramic tape, Figure 5(a), is immersed in a hydrofluoric acid solution at a temperature range of about 85°C to about 95°C. The outer layers begin to separate from the middle layer, and ultimately peel away, as illustrated in Fig 5(b) and (c). The top and bottom layers removed are very thin and brittle; the remaining center layer, due to the

homogeneity of the particles, is uniform, elastic and suitable for use as a membrane within the pressure transducer.

The material removal rate and smoothness of the remaining layer is affected by various factors such as the concentration of HF acid, temperature of the solution, orientation of the sample in the solution, and type of firing process of the ceramic. It has been found that a concentration of 1:4 HF acid in a deionized water solution yielded the fastest and most desirable results. The temperature range of between 85°C and 95°C was most suitable for etching both partially sintered and sintered pieces. The etching rate at this temperature rate using a 1:4 HF acid-deionized water solution was found to be approximately 0.2 micrometers per minute. As in any thermally activated process, lowering the temperature caused the layer splitting to occur too slowly; the HF solution disintegrated all of the material before layers could be separated. Higher temperatures caused the reaction to occur too quickly, yielding a membrane with small and uneven thickness. A time of 20 to 25 minutes was found to be sufficient to exfoliate a partially sintered sample, and 30 to 35 minutes sufficed for a sintered sample. An additional factor which affected the exfoliation rate was whether the HF solution was reused. If the sample was soaked in fresh HF solution, this may begin to occur after about 15-18 minutes. If a previously used amount of HF is used again, the peeling may occur earlier, around 8 to 10 minutes. For this reason, it is believed that the residues of the exfoliation process catalyze the chemical reaction.

In general, the exfoliation process yields thin, elastic membranes of about 50 to 150μm in thickness. The 50 to 65μm membranes are difficult to manipulate. It has been found that 75 to 150μm membranes are suitable for use in a pressure transducer.

The ceramic tape can easily be used to construct three-dimensional forms using laminating and shaping techniques. In order to preserve the probable strength and temperature resistance of the remaining ceramic layers in the device, the joining method must be able to withstand the same or similar conditions as ceramic itself. Transducers fabricated from either fully-sintered to partially sintered, fully-sintered to fully-sintered, partially sintered to partially sintered can be joined by various bonding schemes such as glass frit and water or glass frit and an organic binder. In the preferred embodiment, two partially sintered pieces are joined together with a mixture of glass frit and organic binder and then sintered together. This arrangement seems most capable of preserving the temperature resistance of the material.

Figures 6a and b provide an illustration of a ceramic tape pressure transducer 35 in accordance with the present invention composed of an exfoliated partially sintered ceramic membrane 38 prepared as described above. The pressure of the transducer is measured as a function of the membrane deformation where two piezo-resistors are screen printed. Two piezo-resistors 37a and 37b were used to achieve temperature compensation. Using shrinkage matched paste, nominal thick film technology was used in the screen printing of the piezo--

resistors. The base of the transducer 39 was fabricated using several layers of LTCC tapes, which were laminated and fired. For testing purposes, a vacuum was drawn on the device, as indicated by the arrows in Figure 6b, by means of a vacuum pump.

The LTCC transducer was tested by comparing its response with that of a commercial silicon pressure sensor. The LTCC transducer was tested under temperatures in the range from 25 to 150°C, while the silicon-based sensor was kept at room temperature. The negative pressure applied to the transducer ranged from atmospheric to 100 Torr (one milli-Pascal). The testing set-up consists of a vacuum line which supplied negative pressure to the ceramic transducer. It lies on a vacuum chuck coupled through an o-ring, and adjacent to commercially available silicon piezo-resistive pressure transducer. An attached PC collects data on the measured change in voltage over time as the pressure is raised and lowered through a valve.

Figure 7 provides the results of the comparative testing. As Figure 7 shows, one can infer that the response time of the LTCC sensor is faster that the open-close time for the valves in the testing manifold (-0.27 seconds).

EXAMPLE III: MINUTE VALVE

An additional embodiment of the present invention includes meso-scale valves to be used in ceramic tape based integrated systems. These devices can be fabricated entirely of ceramic tape layers, or integrate other material layers forming a hybrid device. One such device 40, comprises, among other things, a multilayer coil 41, a fluidic system 42 comprising an

inlet port 43 and outlet port 44 and a flexible diaphragm 45, having a bonded magnet 46, constituting a media interface, as shown in Figure 8. Each subsystem can be manufactured separately then integrated into a unitary device. Device dimensions are in the meso or intermediate range with the smallest features such as the fluid conduit in the manifold of 400μm and the largest features, such as an actuating coil, of 15mm.

Figure 9 depicts the various steps of the fabrication process for a flexible diaphragm sub-system which can be integrated into the valve device. Flexible diaphragms, when used with a rare earth magnet, allows for electromagnetic actuation of the device. This subsystem can be formed according to the following steps: (a) thickness definition by diffusion, (b) aluminum mask deposition, (c) spring geometry definition, (d) silicon plasma etching to form vias, (e) cleaning and Si nitride deposition, (f) definition of area and RTV dispensing by employing photoresist layers, (g) backside anisotropic etching and diaphragm release, and (h) cleaning and magnet bonding. This design is implemented using silicon technology of the present art for a square spiral spring that is covered with an polysiloxane film.

An additional subsystem that can be independently assembled is an actuating coil. Figure 10 displays actuating coil geometry 52 and layer interconnection 54 of a fabricated device 55. The hybrid coil consists of several layers of planar spiral coils such as layers 50 and 51 in Figure 11. In a preferred embodiment, a square spiral coil of 1 x 1 cm^2 is designed to have a small quantity of interconnecting vias and

connected so as to preserve the magnetic field direction. A single layer was designed to have silver conductors of 80μm lines and 10μm thickness with 80μm space between lines, rendering a 20 turn single layer coil. The total coil resistance is high (120 Ohms). The coil resistance can be lowered by using tape machining techniques to obtain 60μm thickness. Due to coil high resistance, thermal consideration limits the current to 150 mA. Vias of 250μm were used to ensure layer interconnection. A five and eight layer coil have been fabricated using DuPont 951 Green Tape™ and the aforementioned method. The silver spiral coils or grooves can be machined into green tape or screen printed onto the tape.

The fluidic subsystem 47, including valve opening 48, was also fabricated at the same time using separate LTCC green tape layers.

These actuating coil and fluidic subsystems were combined with the anisotropically etched silicon rectangular planar spring and a high-energy product SmCo permanent magnet to form a hybrid device. The multilayer actuating coil and fluidic subsystem, are aligned, stacked, laminated and sintered together to form a LTCC substrate. The above-described flexible diaphragm is bonded to the LTCC substrate using a dispensed gasket of polysiloxane, which also serves to maintain the appropriate spacing between the center coil and magnet which is about 300μm. A polysiloxane valve seat 49, as shown in Figure 8, is also deposited onto the top layer, with a controlled dispenser to prevent valve leak. The hybrid device consists of 5 layers of planar spiral coils. The total coil resistance of the device

tested was 120 Ohms. A 200 micrometers deflection of the silicon 30μm thick rectangular planar spring with polysiloxane sealing was obtained using a 900 Gauss SmCo magnet (1μm diam).

Alternative embodiments of the valves of the present invention may include valves which are normally in the open position or valves which are normally in the closed position. Yet other valves may have variable or partially open position operation due to a fluctuation in the current within the electromagnetic coil. The valve opening is tied to the fluctuation in electric current.

EXAMPLE IV: MINUTE ELECTROMAGNETIC PUMPS

Two separate embodiments of minute electromagnetic reciprocating diaphragm pumps were designed and fabricated using LTCC tapes and polyimide film. Figure 11 depicts schematically the major components of the first pump embodiment. Several layers of ceramic tapes were used to form the pump chamber 60. Two passive valves 66a and 66b were made out of Kapton™ polyimide film. The diaphragm 67, also made out of Kapton™, was bonded to the ceramic substrate 61 with epoxy. Glass tubes 63' and 64' were then bonded to the inlet port 63 and outlet port 64, respectively, to facilitate flow rate measurements and the introduction of back-pressure. The permanent magnet 69 can be placed either below the diaphragm 67 or above it, with appropriate spacers between the diaphragm and the magnet.

In the second design, two Kapton diaphragms 167 and 167' were used to cover the chamber 160 as shown in Figure 12. Rather than having one moving diaphragm, two diaphragms were

mounted on ceramic substrate 161 in order to increase the flow output. The inlet (not shown) and outlet 164 openings were machined directly in the Kapton film and the passive valves for the inlet 166a and outlet (not shown) openings were bonded adjacent to the openings. The two coils on each of the two diaphragms, formed as described below, were connected through a via in the ceramic layer in such a way that the currents in the coils flowed in opposite directions. Opposite current directions produced opposite forces on the diaphragms. Inlet and outlet tubes 163' and 164' were provided in fluid communication with the inlet and outlet, respectively. In this embodiment also, magnet 169 may be positioned above or below the diaphragms.

A. Fabrication Techniques

1. Pressure Chamber and Passive Valve Fabrication

Figure 13a depicts the fabrication of the pressure chamber and passive valves. In the first step, two (2) layers of LTCC 61 and 62 were laminated and machined to form a 2cm x 2cm x 500μm chamber. The 0.45mm diameter inlet 63 and outlet 64 openings were machined in a third layer. In the second step, all layers were laminated together and co-fired to form a single monolithic structure 65. In the third step, Excimer micromachining laser system was used to fabricate 13μm thick 0.7mm x 5mm rectangular Kapton passive flap valves 66a and 66b. The Kapton valves were placed over the inlet and outlet openings and bonded to the structure with epoxy.

2. Diaphragm Fabrication

Figure 14 shows the processing steps for the fabrication of electromagnetic coils on the copper-coated

Kapton™ diaphragm using photolithographic method. A 25mm x 25mm x 30μm thick Kapton™ film with 5μm thick copper coating (Gould Electronics) on both sides was used. The copper surfaces were cleaned with alcohol and DI water, and dried with air. In step 1, positive photoresist was spin-coated at approximately 4000 rpm for 25 seconds on one surface. It was then dried for 2 minutes at 115°C. The other copper surface was then spin-coated with positive photoresist and dried at 115°C for 2 minutes. A small indent was made at the center of the Kapton for top and bottom surface alignment during the UV light exposure. The indent was used to align the center of the coils. In step 2, the surfaces were exposed to UV light with a coil mask on top of the surface. The other side was exposed in such a way as to ensure that the current in both coils will flow in the same direction. This is important since opposite current directions would cancel the forces created by the two coils. In step 3, after UV exposure, an indent was punched through to form a via (170a and 170b in Figure 12) between the top and the bottom coils. In step 4, the photoresist was then developed leaving photoresist of coil-shape on top of the copper surfaces. The copper was then etched with copper etching solution. The chromium coating was etched with potassium permanganate/sodium hydroxide solution and oxalic acid solution. In step 5, the remaining photoresist was stripped with photoresist stripper. Next, the via was filled with copper paste. Electrical connections to the coils were then attached. The diaphragm contained 20 coils in an area of 2cm x 2cm. The width and the spacing of the coils were 200μm.

3. Bonding of the Components

After fabrication of the pressure chamber with passive valves and the diaphragm was completed, as described above, the pressure chamber and the electromagnetic coil-containing diaphragm were bonded to form the pump. A glass tube 63' was bonded to the inlet hole. Tygon tubing was connected to the glass tube. Epoxy was used for bonding. NdFeB magnet 69 of 1.26 x 0.66 x 0.39 inches (32mm x 16.76mm x 9.91mm, Edmund Scientific) was disposed below the diaphragm 67. Spacers were placed between the diaphragm and the magnet to allow room for the diaphragm's deflection. The distance between the magnet and the diaphragm was about 0.5mm.

The second pump embodiment was fabricated using the same methods, with two diaphragms, rather than one. The inlet and outlet ports on one Kapton diaphragm were machined with Excimer laser. Kapton flap valves were bonded over the openings.

B. **Performance Testing**

Testing was carried out to evaluate the first pump's performance. A function generator (Tektronix GFG250) was used to apply time-stepped signal to an amplifier. The amplifier was used to increase the magnitude of the power. Typically, 190 mA of RMS current was applied to the coils. The resistance of the two coils connected in series and mounted on the Kapton diaphragm was 45Ω. A water slug was introduced at the inlet of the Tygon tubing of 1/16 (1.59mm) diameter that was connected to the inlet port. The tube was vertical so that the water slug flowed against gravity. Once steady state conditions were achieved, the distance traveled by the slug during a 15 seconds period was

measured to obtain the flow rate. Each measurement was repeated six times.

By measuring the distance traveled by the water slug in the vertically clamped Tygon tubing, air-pumping flow rate was calculated for the first pump design. Figure 15 shows the flow rate as a function of actuation frequency. The vertical bars indicate the scatter of the data. The circle represents the average of six measurements. As the actuating frequency increased, the flow rate increased, attained a maximum, and then decreased. The maximum airflow rate was about 1.7 mL/min at 50 Hz.

The results obtained were not as good as would be expected if the pump's design and operation conditions had been optimized, which was not the case in this test. These preliminary results show, however, that the hybrid pumping devices of this invention are viable components for use in meso-scale chemical and biological analysis systems, the so-called "lab-on-a-chip". Several design factors can be improved to enhance performance of the pumps, such as using thinner Kapton diaphragms to achieve larger deflections, using better size and placement of the permanent magnet to achieve larger forces, using electromagnetically actuated valves to reduce leakage, and the optimizing of coil dimensions to reduce stiffness of the diaphragm.

The operation of the first pump embodiment is illustrated schematically in Figure 16. Figure 16a shows the charge cycle, in which the interactions between the electromagnetic coils 70 formed on diaphragm 71 and magnet 73

attract the diaphragm toward the magnet; and Figure 16b shows the discharge cycle in which magnetic force repels the diaphragm 71 from magnet 73. The direction of fluid flow in each cycle is indicated by the arrows. Figure 16 also shows an alternative for controlling operation of the inlet and exit port valves of the pump chamber. As depicted in Figure 16, electromagnetic coils 75a and 75b may be formed on each of the check valves. In this design, the same magnetic force that produces deformation of the diaphragm can be caused to open and close the check valves.

The principles employed in the two diaphragm pumps described immediately above may be adapted to the design of a peristaltic pump and/or stirrer. Thus, traveling waves with the same amplitude and frequency but opposite phase maybe transmitted in membranes and induce peristaltic motion in the fluid. The peristaltic pump/stirrers includes a fluid-filled cavity bounded from below and above by flexible membranes or diaphragms. By forming electrical conductors on these membranes and passing electrical currents through these conductors in the presence of a magnetic field, the membranes can be caused to vibrate with relatively large amplitudes and in a pre-determined way. Since the conductors can be shaped using photolithography, fairly complicated motions can be induced in this way. For example, by appropriate phasing of the current, one can induce traveling waves in the membrane, which, in turn, will cause peristaltic pumping in the fluid. The construction of membranes made out of Kapton having electromagnetic coils formed thereon, has already been described in detail.

The intensity of magnetic fields associated with the electromagnetic devices described herein may be increased by the inclusion in the devices of "soft" i.e. easily magnetized and demagnetized material. This can be accomplished, for example, by plating surfaces with such material, as shown in Figure 4d, by embedding soft magnetic material 81 in cavities 83 formed in the ceramic tapes 85, as shown in Figure 17, or by preparing ceramic tape formulations from magnetic oxides. Magnetic materials that are suitable for this purpose include, without limitation, ferrites magneto plumbites permalloy and the like.

While certain embodiments of the present invention have been described and/or exemplified above, various other embodiments will be apparent to those skilled in the art from the foregoing disclosure. The present invention is, therefore, not limited to the particular embodiments described and/or exemplified, but is capable of considerable variation and modification without departure from the scope of the appended claims.

What is claimed is:

1. An electromagnetic actuation device comprising:
   a. a flexible member adapted to be supported by one part and to be deflected at a second part upon actuation;
   b. a first ceramic layer supporting said one part of the flexible member; and
   c. a second ceramic layer comprising at least one electromagnetic coil and at least one contact member for effecting current flow through said electromagnetic coil, said coil being positioned adjacent said flexible member, at least the second part of said flexible member having magnetic properties so as to be deflected upon current flow through said coil, and, optionally,
   d. at least one other ceramic layer comprising at least one electromagnetic coil and at least one contact member to effect current flow through each electromagnetic coil of said at least one other ceramic layer, said contact members being operable to activate said device by the flow of current through said coils, thereby effecting actuation of said flexible member.

2. An electromagnetic actuation device according to claim 1, wherein said electromagnetic coil of said second ceramic layer is substantially co-extensive with said

electromagnetic coil of said at least one other ceramic layer.

3. An electromagnetic actuation device according to claim 1, wherein said flexible member comprises an elongated beam having a magnet at said second part.

4. A device according to claim 3, wherein said flexible member is non-magnetic.

5. An actuation device according to claim 1, wherein said flexible member is an elongated beam of soft magnetic material.

6. An electromagnetic actuation device according to claim 1, wherein at least one of said ceramic layers comprises multiple plies of low temperature co-fired ceramic tape.

7. A minute pump having an inlet, an outlet, a pump cavity with first and second check valves, which control the opening of said inlet and said outlet, respectively, and at least one flexible diaphragm adapted to be reciprocated to deflect into the cavity, said pump comprising:

   a. a first ceramic layer having said pump cavity therein; said at least one flexible diaphragm member being supported on said first ceramic layer overlying said cavity, and comprising at least one electromagnetic coil;

b. a magnet positioned in relation to said at least one flexible diaphragm member to provide a magnetic force effecting reciprocation of said member upon current flow through said coil; the valves operating to permit fluid flow through the cavity upon reciprocation of said flexible member.

8. A pump according to claim 7, wherein said check valves are passive valves.

9. A pump according to claim 7, wherein said check valve are electromagnetically operated.

10. A pump according to claim 7, including a second flexible member mounted on said first ceramic layer, said first and second flexible members being disposed on opposite sides of said cavity, each of said flexible members comprising an electromagnetic coil, said coils being interconnected to provide current flow in opposite directions to effect opposite forces on the flexible members.

11. A pump according to claim 10, wherein at least one of said flexible members constitutes the mount for said check valves.

12. A pump according to claim 7, including a second ceramic layer mounted on said first layer on the side opposite said

flexible member, said check valves being mounted on said second ceramic layer.

13. A pump according to claim 7, wherein said check valves comprise a polyimide film.

14. A pump according to claim 7, wherein said magnet is a permanent magnet having a pole face substantially coextensive with said electromagnetic coil.

15. A pump according to claim 7, wherein at least one of said ceramic layers comprises multiple plies of low temperature co-fired ceramic tape.

16. A pump according to claim 7, which further includes a mass of soft magnetic material which is effective to increase the intensity of said magnetic force.

17. A minute valve having a body member comprising at least first and second ceramic layers defining a flow channel, with an inlet port and an outlet port for transporting fluid through said flow channel, and a valve opening positioned in said flow channel between said inlet port and outlet port; a flexible diaphragm member having a flexed condition engaging said valve opening and an unflexed condition disengaging said valve opening, engagement of said valve opening by said flexible diaphragm member interrupting fluid transport through said flow channel; a

base member comprising at least one other ceramic layer having at least one electromagnetic coil; and a magnet mounted on said flexible diaphragm member to provide a magnetic force that causes said diaphragm to assume said flexed condition upon current flow through said electromagnetic coil.

18. A valve according to claim 17, having a base member comprising multiple ceramic layers with at least one electromagnetic coil disposed therein.

19. A valve according to claim 17, wherein said magnet is a permanent magnet which is mounted in registry with said valve opening.

20. A valve according to claim 17, wherein at least one of said ceramic layers comprises multiple plies of low temperature co-fired ceramic tape.

21. A valve according to claim 17, which further includes a mass of soft magnetic material which is effective to increase the intensity of said magnetic force.

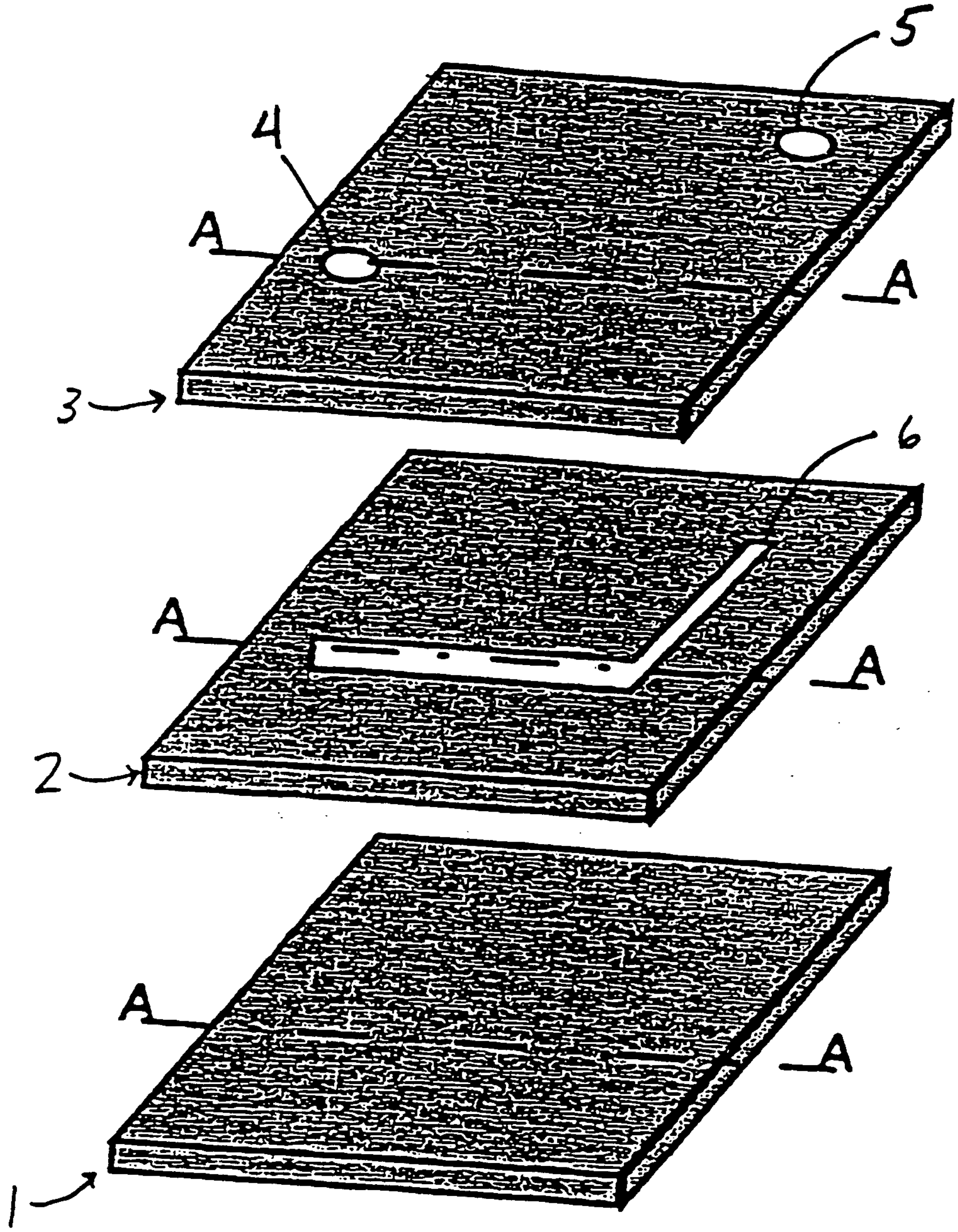
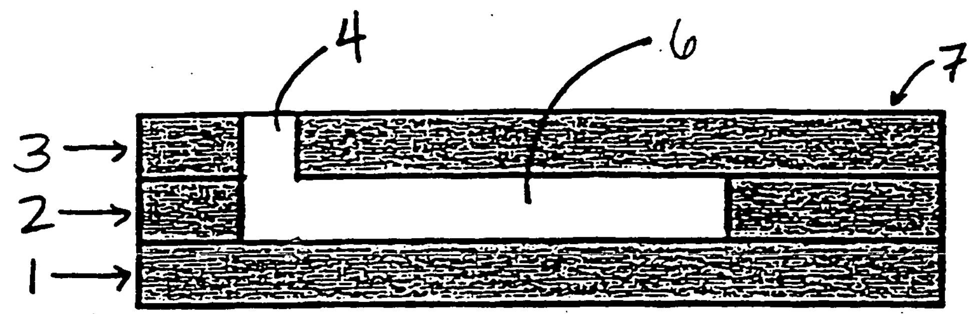


Figure 1a



Cross-section A-A

Figure 1b

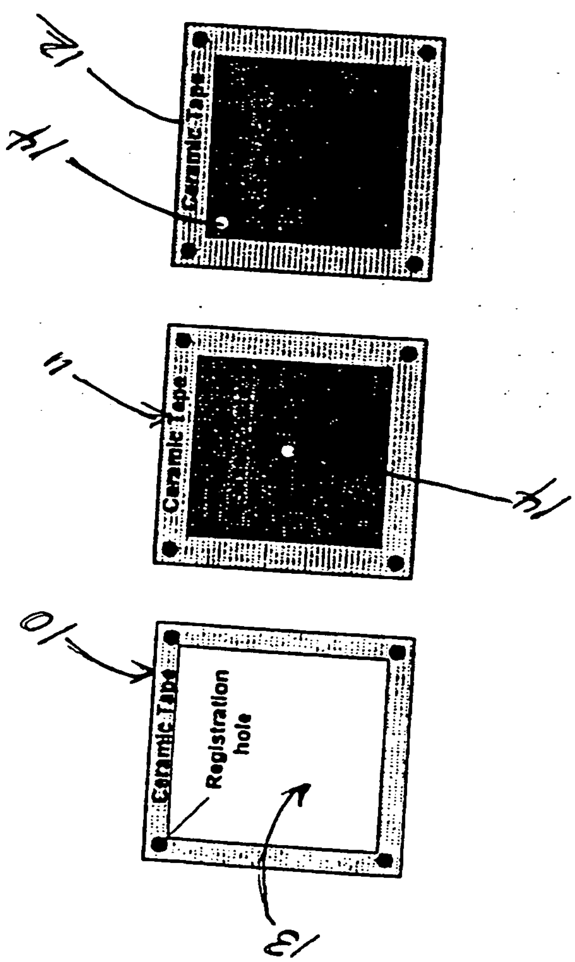

Ceramic Tape
Ceramic Tape
Ceramic Tape
Registration hole
10
11
12
13
14
14

FIG. 2a

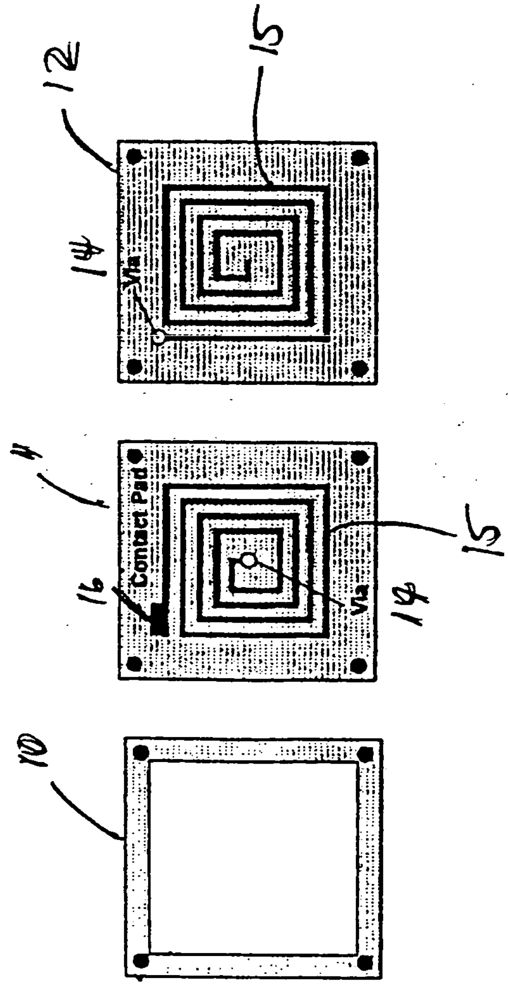


FIGURE 2b

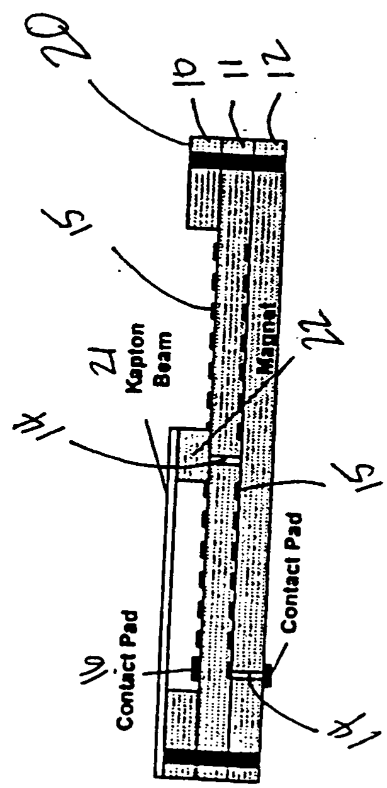

20
10
11
12
15
Kapton Beam
21
Magnet
22
14
15
Contact Pad
16
Contact Pad
14

FIG. 3a

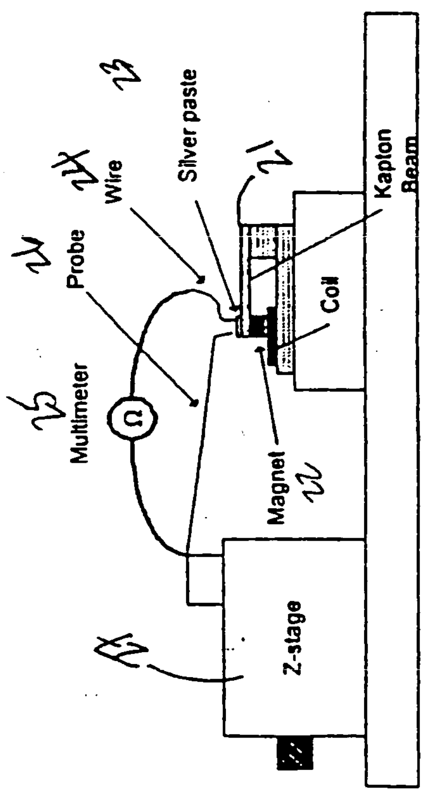

Multimeter
Ω
Probe
Wire
Silver paste
Kapton
Beam
Coil
Magnet
Z-stage

FIG. 3b

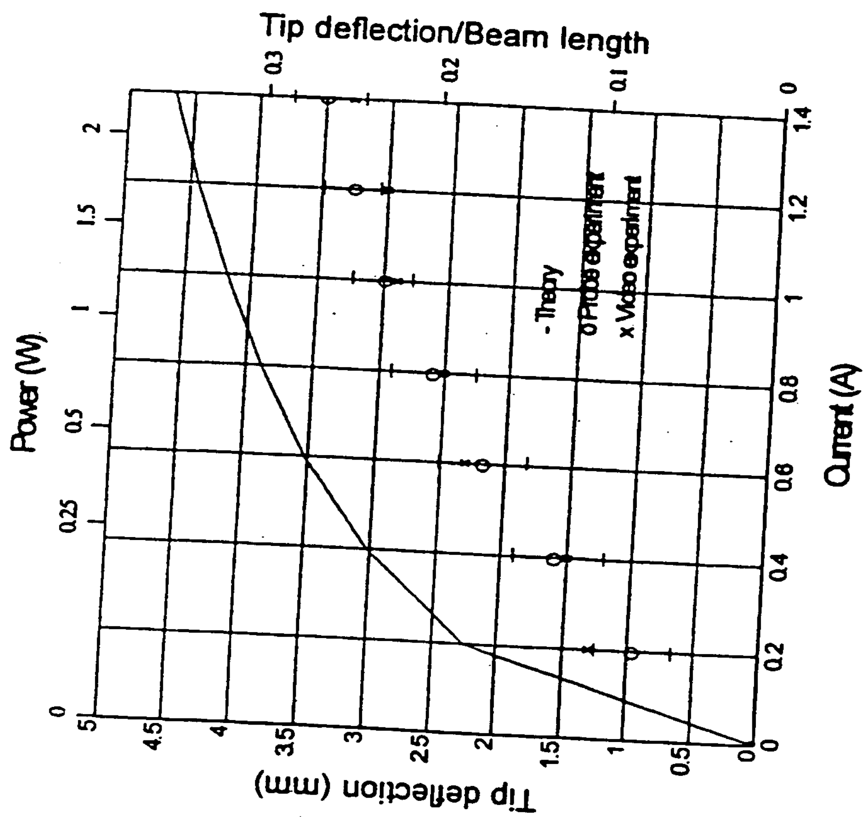

Tip deflection/Beam length
Power (W)
Current (A)
Tip deflection (mm)
- Theory
o Probe experiment
x Video experiment

FIG. 3c

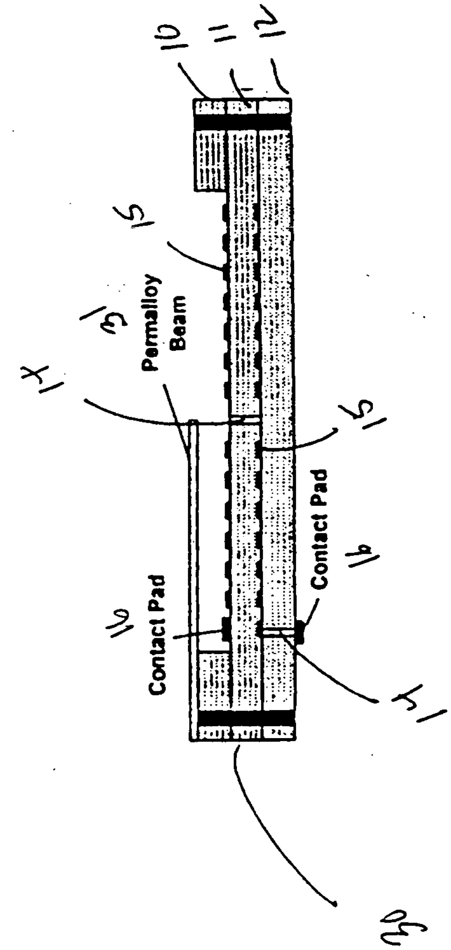

10
11
12
15
13
Permalloy Beam
17
15
Contact Pad
16
Contact Pad
16
14
20

FIGURE 4a

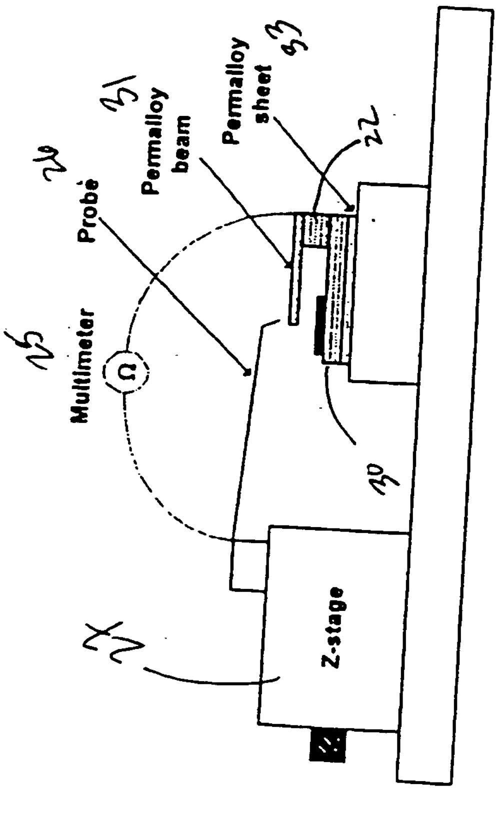


FIGURE 4b

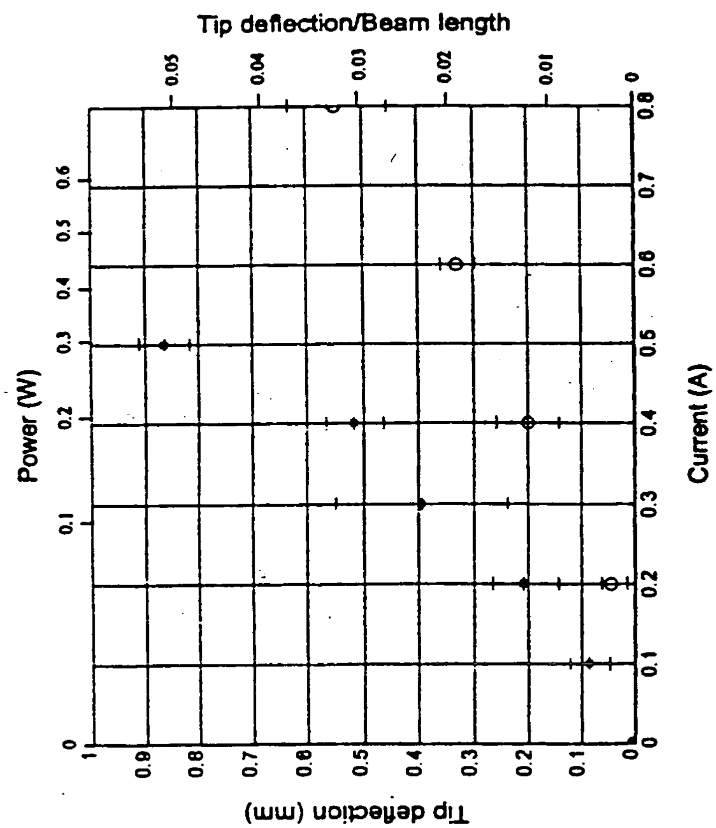

Tip deflection/Beam length
0.05
0.04
0.03
0.02
0.01
0
Power (W)
0
0.1
0.2
0.3
0.4
0.5
0.6
Current (A)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
Tip deflection (mm)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

FIGURE 4c

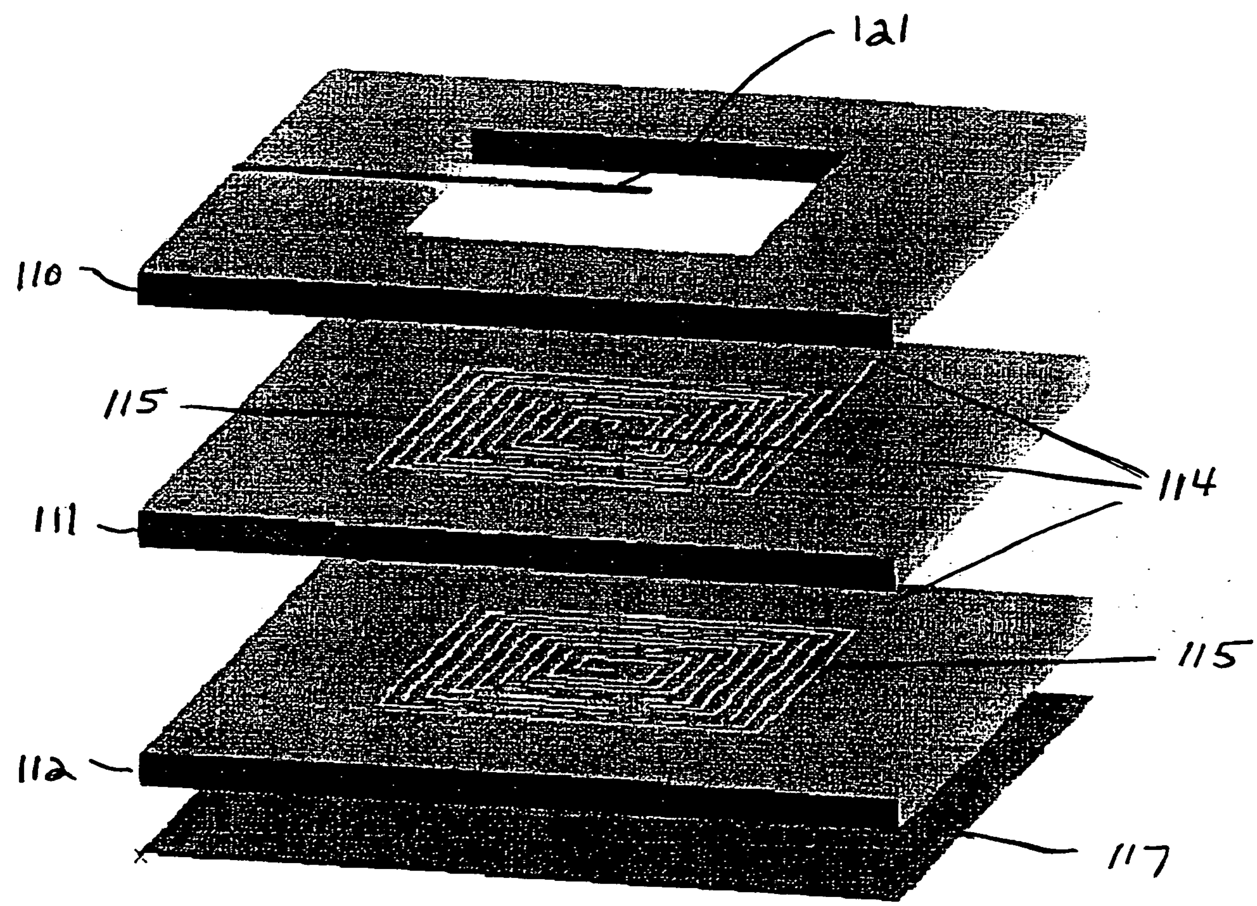


Figure 4d

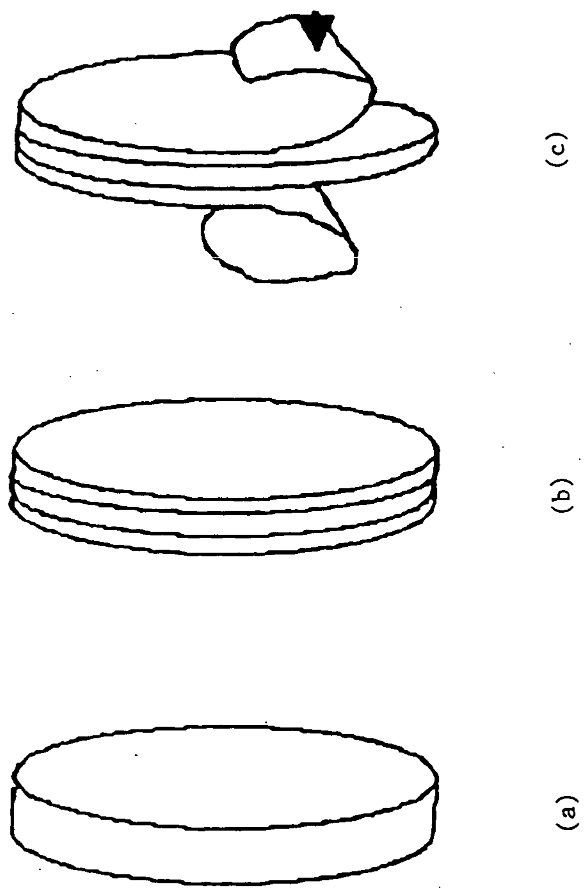


FIGURE 5

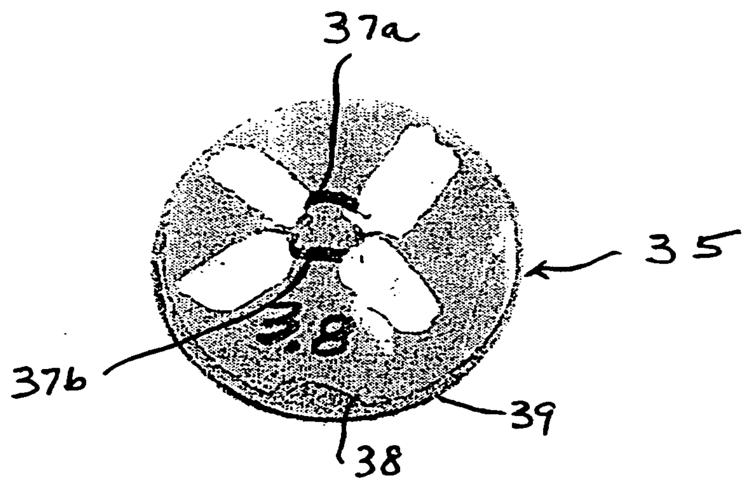


Figure 6a

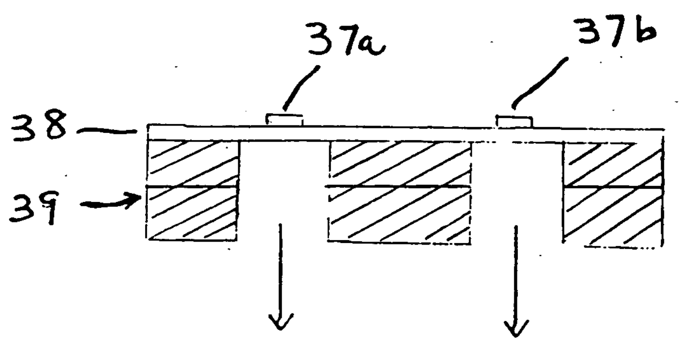


Figure 6b

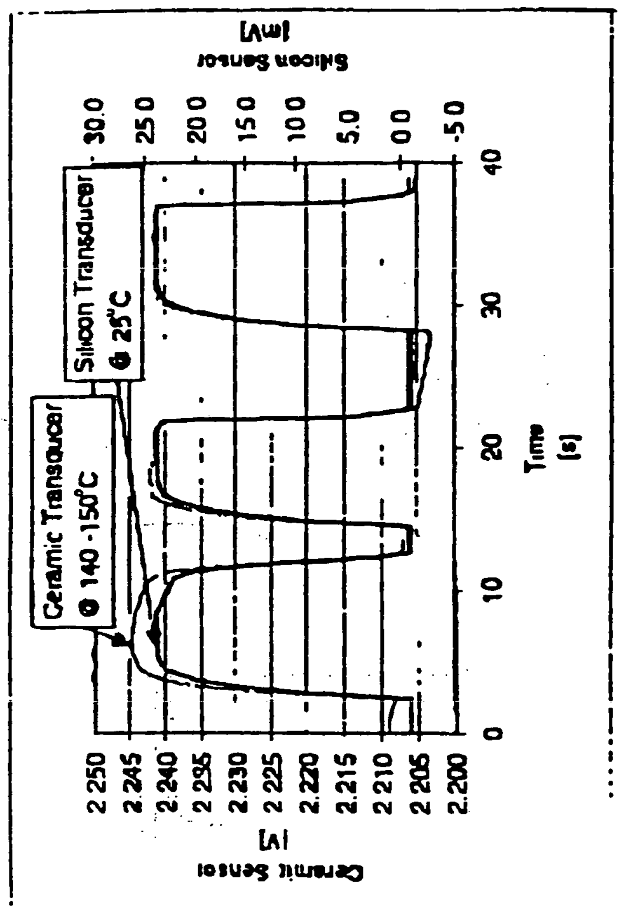

Ceramic Transducer
@ 140-150°C
Silicon Transducer
@ 25°C
Time
[s]
0
10
20
30
40
2.250
2.245
2.240
2.235
2.230
2.225
2.220
2.215
2.210
2.205
2.200
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
Silicon Sensor
[mV]

FIGURE 7

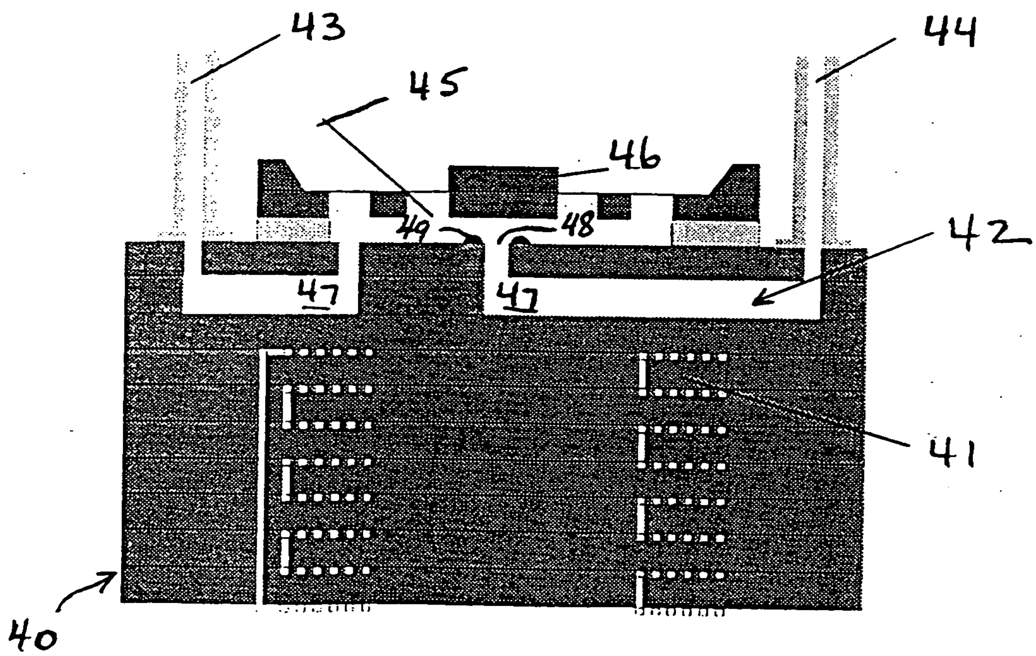


Figure 8

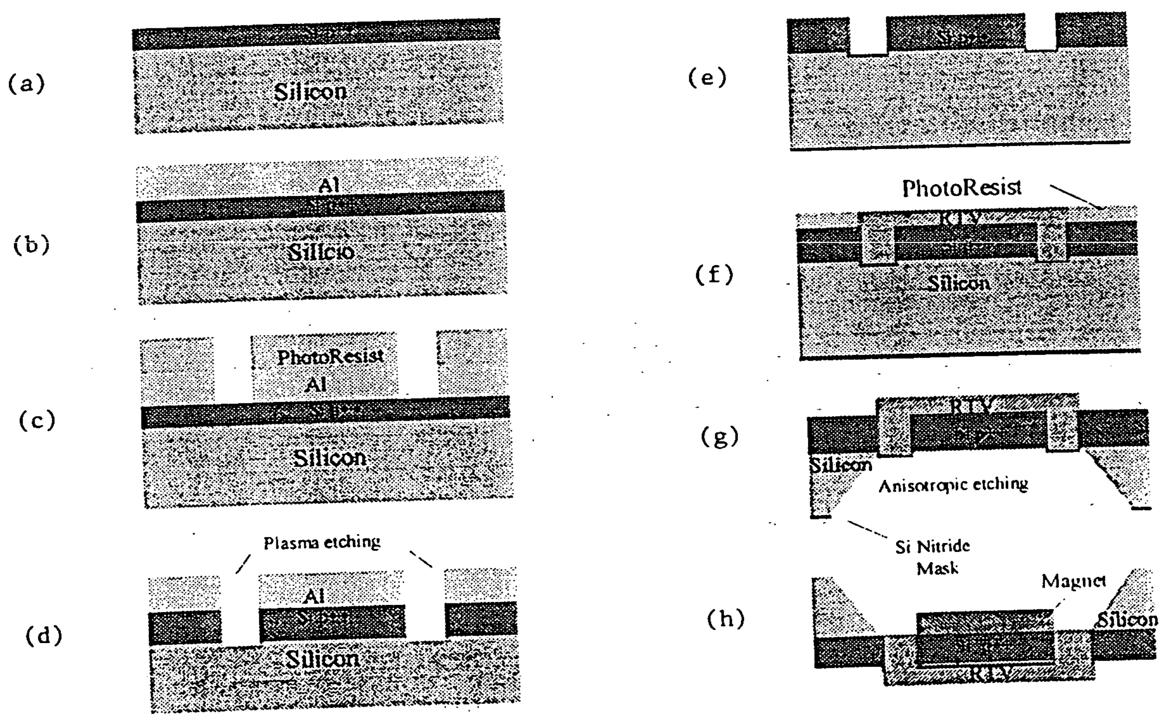

(a)
Silicon
(b)
Al
Silicio
(c)
PhotoResist
Al
Silicon
(d)
Plasma etching
Al
Silicon
(e)
(f)
PhotoResist
RTV
Silicon
(g)
RTV
Silicon
Anisotropic etching
Si Nitride
Mask
(h)
Magnet
Silicon
RTV

Figure 9

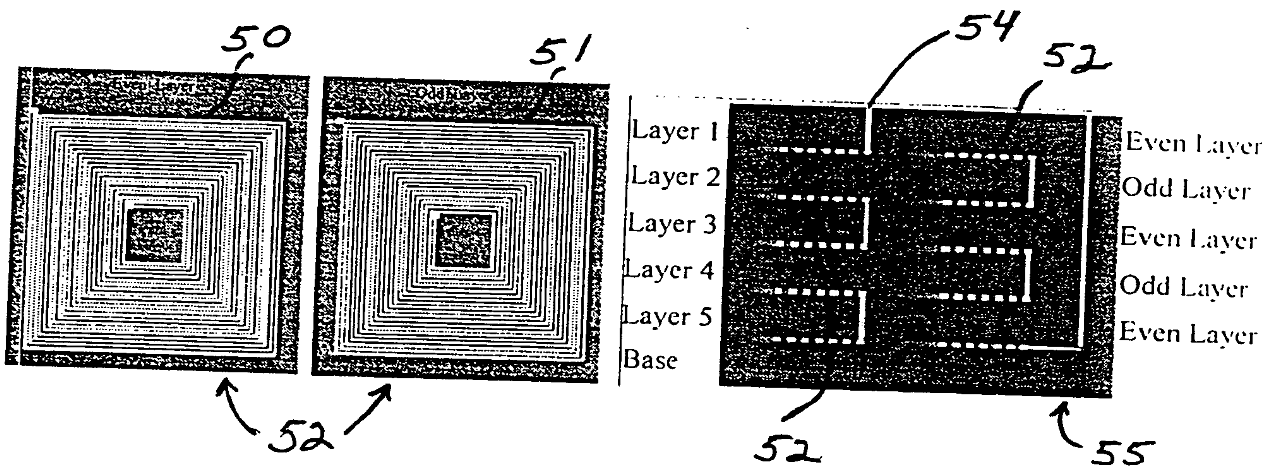

50
51
54
52
Layer 1
Layer 2
Layer 3
Layer 4
Layer 5
Base
Even Layer
Odd Layer
Even Layer
Odd Layer
Even Layer
52
52
55

Figure 10

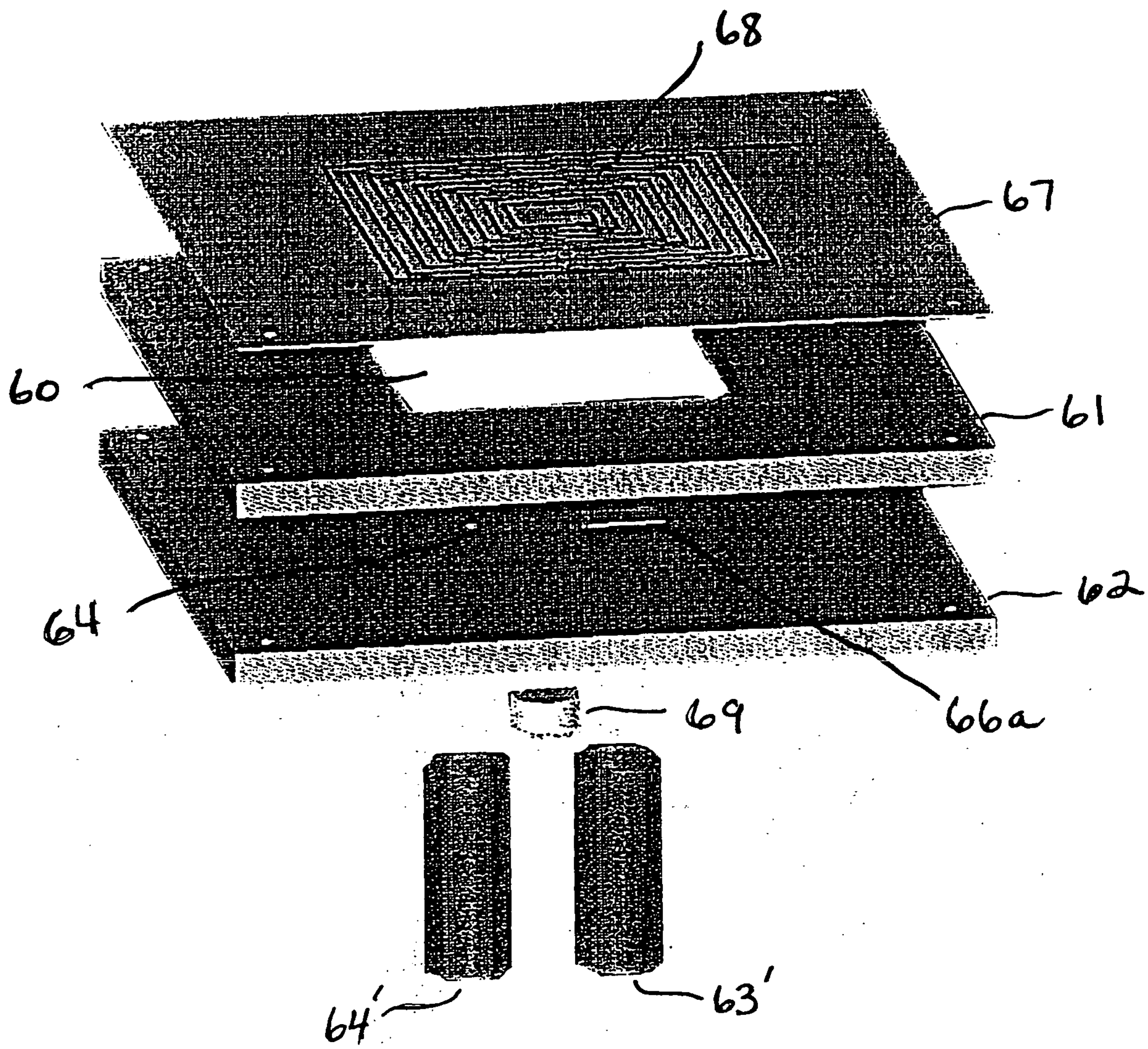


Figure 11

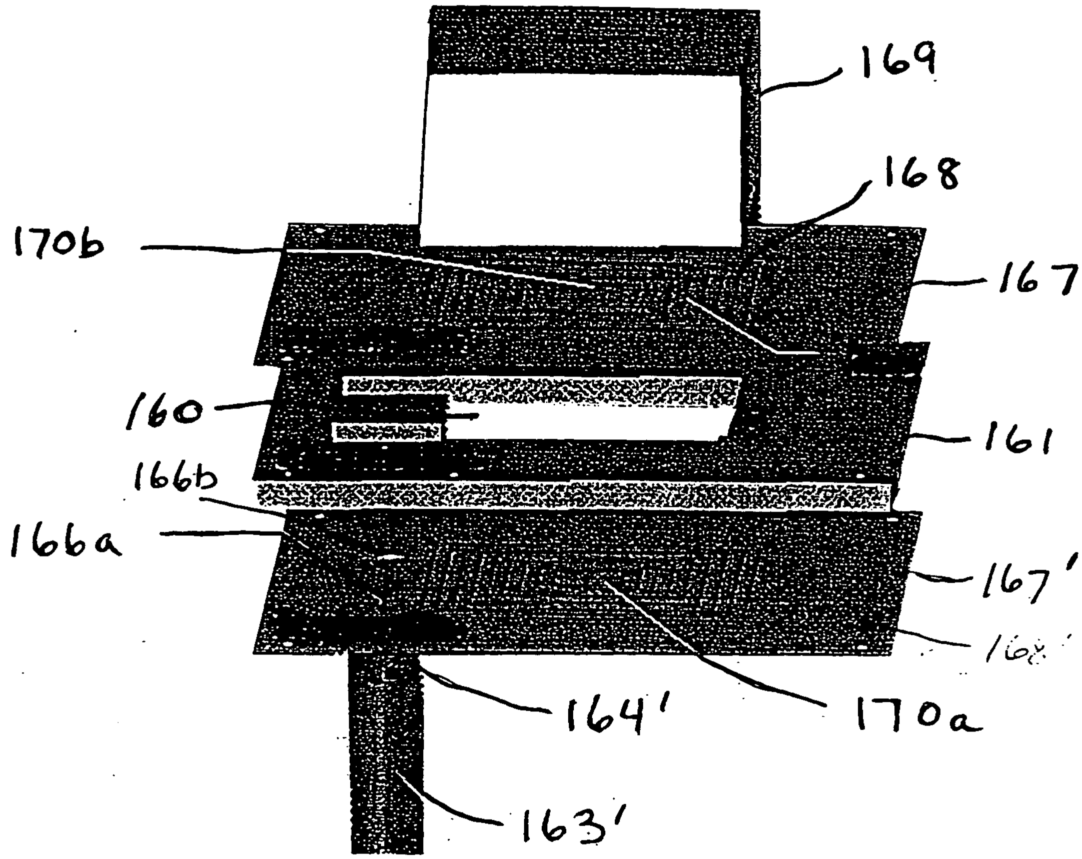


Figure 12

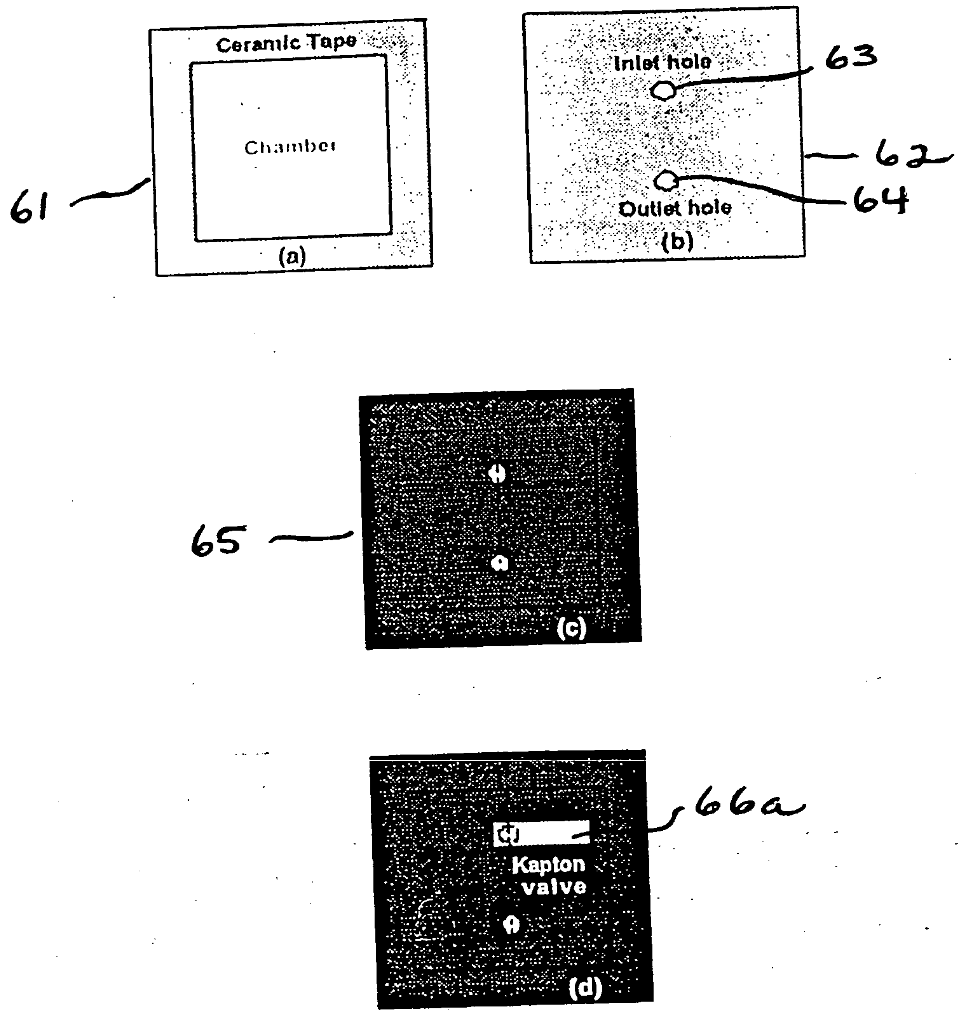


Figure 13a

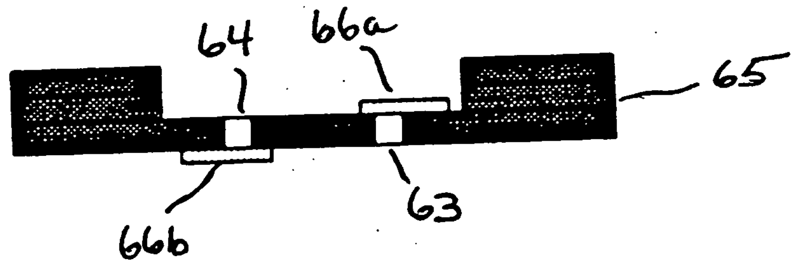


Figure 13b

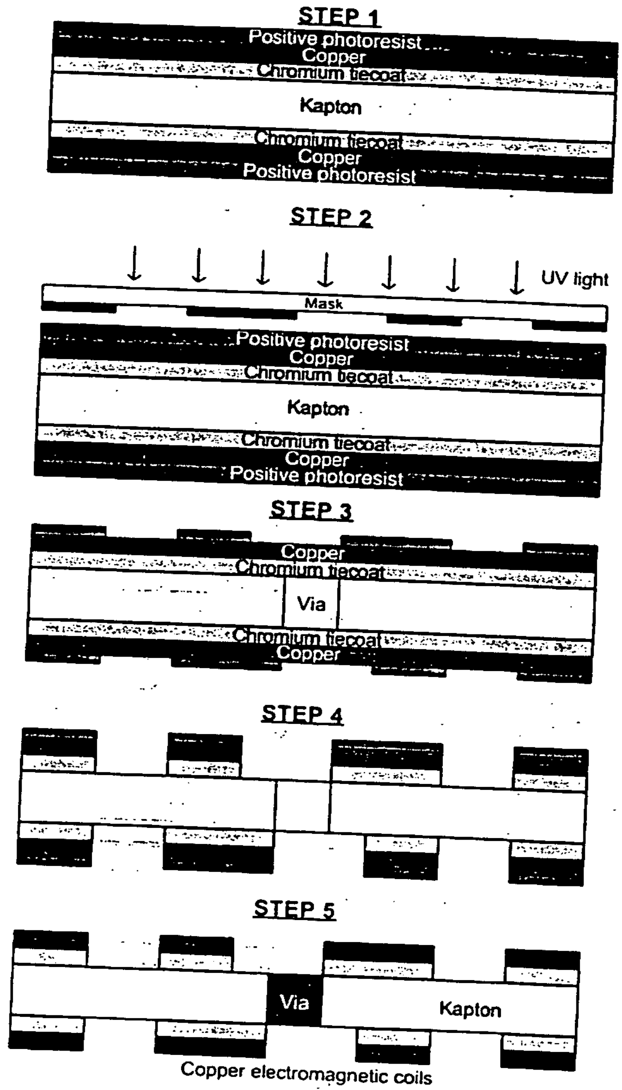

STEP 1
Positive photoresist
Copper
Chromium tiecoat
Kapton
Chromium tiecoat
Copper
Positive photoresist
STEP 2
UV light
Mask
Positive photoresist
Copper
Chromium tiecoat
Kapton
Chromium tiecoat
Copper
Positive photoresist
STEP 3
Copper
Chromium tiecoat
Via
Chromium tiecoat
Copper
STEP 4
STEP 5
Via
Kapton
Copper electromagnetic coils

Figure 14

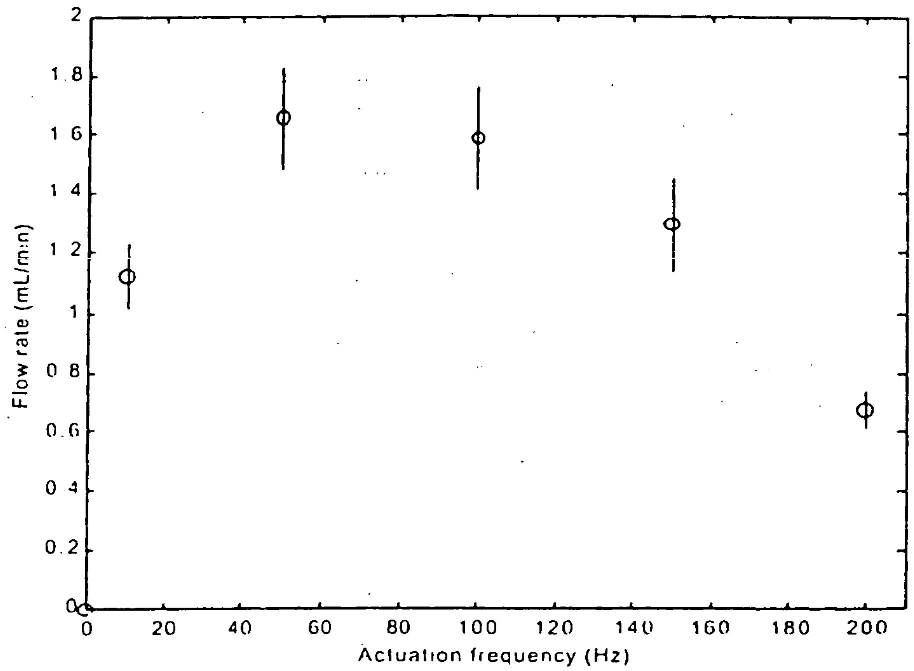

2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Flow rate (mL/min)
0
20
40
60
80
100
120
140
160
180
200
Actuation frequency (Hz)

Figure 15

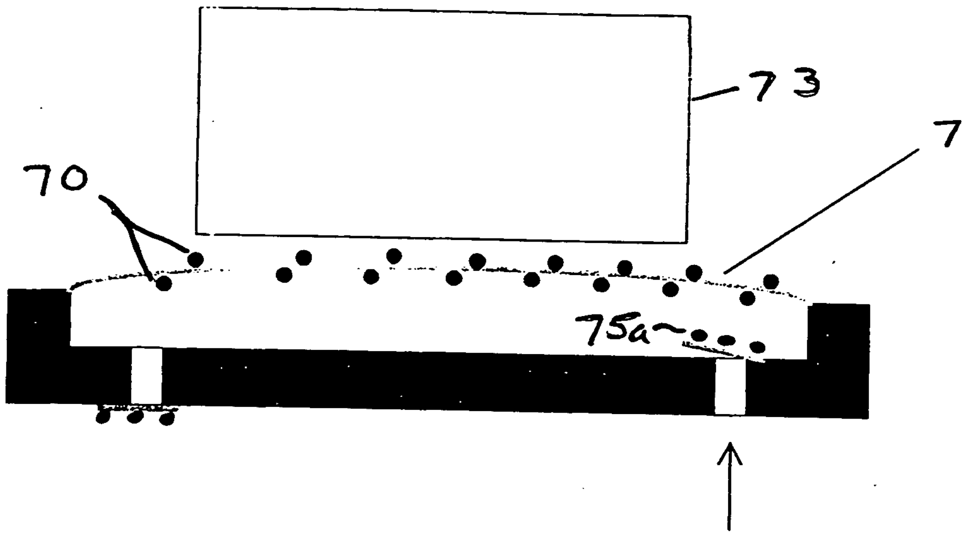


Figure 16a

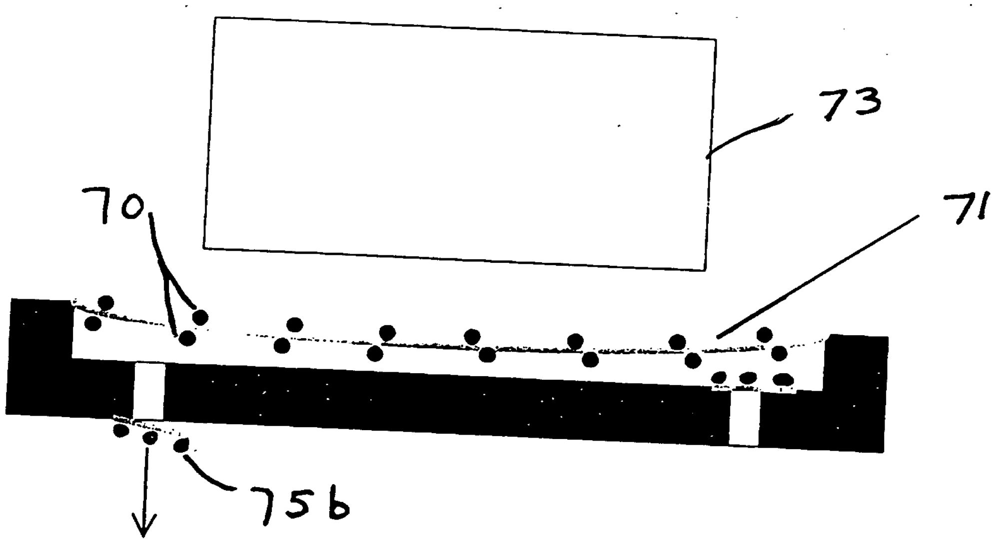


Figure 16b

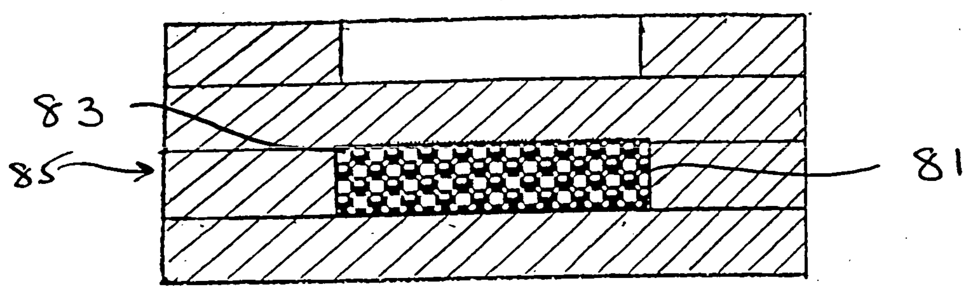


Figure 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/30441

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01P 1/10; H01H 51/22
US CL : 335/4, 78-86, 124, 128; 333/262, 101

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 335/4, 78-86, 124, 128; 333/262, 101

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,889,452 A (VUILLEUMIER) 30 March 1999, 30.03.1999), see entire document.	1-21
Y	US 5,847,631 A (TAYLOR et al.) 08 December 1998 (08.12.1998), see entire document.	1-21
Y	US 5,652,559 A (SAIA et al.) 29 July 1997 (29.07.1997), see entire document.	1-21
Y	US 5,467,068 A (FIELD et al.) 14 November 1995 (14.11.95), see entire document.	1-21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search
31 January 2001 (31.01.2001)

Date of mailing of the international search report
04 APR 2001

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(74) Agents: **HAGAN, Patrick, J.** et al.; Dann Dorfman Herrell and Skillman, P.C., Suite 720, 1601 Market Street, Philadelphia, PA 19103 (US).

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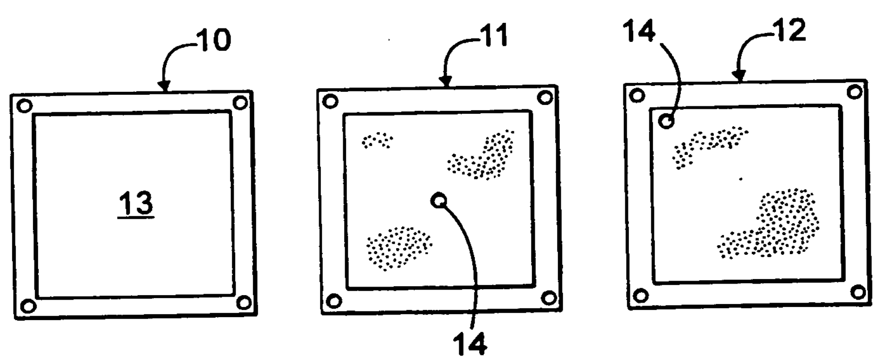
For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: MINUTE ELECTROMECHANICAL ACTUATION AND FLUID CONTROL DEVICES AND INTEGRATED SYSTEMS BASED ON LOW TEMPERATURE CO-FIRED CERAMIC (LTCC) TAPE TECHNOLOGY



(57) Abstract: Disclosed are minute electromechanical devices (10, 11, 12), as electromagnetic actuators, pressure transducers, pumps and valves, which are conveniently fabricated from ceramic tape to yield monolithic ceramic and hybrid structures.

WO 01/035484 A1

MINUTE ELECTROMECHANICAL ACTUATION AND FLUID CONTROL DEVICES AND INTEGRATED SYSTEMS BASED ON LOW TEMPERATURE CO-FIRED CERAMIC (LTCC) TAPE TECHNOLOGY

Cross-Reference to Related Application

This application claims the benefit of U.S. Provisional Patent Application No. 60/165,180, filed November 12, 1999, the entire disclosure of which is incorporated by reference in the present application as though set forth herein in full.

Field of the Invention

This invention relates to minute electro-mechanical devices, such as electromagnetic actuators, pressure transducers, pumps, relays, valves, and peristaltic pumps and stirrers that are readily fabricated from ceramic tape alone and ceramic tapes in conjunction with non-ceramic materials, such as Kapton™ or the like. The present invention also includes a meso-scale electro-mechanical system that may include one or all of the devices described herein.

Background of the Invention

Silicon technology has made possible the batch manufacturing of highly precise, dense, relatively large scale integrated circuits.

Attempts have been made in the manufacture of meso-scale electro-mechanical devices and systems to exploit silicon as a high precision, high strength, high reliability mechanical material that facilitates the production of components and devices which integrate sensors, mechanical elements and electronic circuits. Experience has shown, however, that the proposed fabrication techniques involve many of the same

disadvantages encountered in the manufacture of silicon-based integrated circuit modules. In general, the fabrication of silicon-based, meso-scale devices and systems requires specialized equipment and highly trained personnel, resulting in substantial capital investment and manufacturing costs. Apart from the relatively high cost, it is difficult to package and interface meso-scale electromechanical devices with one another and to fabricate relatively large, three-dimensional meso-scale structures, particularly those having fluid handling elements.

Other materials of fabrication for meso-scale electro-mechanical devices and systems, such as glass and plastic, have similar drawbacks with respect to the difficulty and cost of manufacture of three-dimensional structures.

Accordingly, a need exists for meso-scale electro-mechanical devices of the type mentioned above, which can be readily integrated into three-dimensional structures and which can be easily and economically manufactured.

Summary of the Invention

The present invention provides minute mechanical, fluid control and electronic devices and integrated systems that are assembled from or utilize structures which are fabricated from ceramic tape, or hybrid structures made of both ceramic tapes and other structural materials, and which may incorporate one or more of the following: actuators, switches, sensors, pressure transducers, thermistors, valves, pumps, stirrers and hydraulic interconnects. All of these devices are fabricated using a technique that allows machining of flow conduits into individual

layers and/or printing of conductors and resistors upon one or more of these layers.

Ceramic tape affords a convenient and versatile medium for the custom fabrication of meso-scale mechanical and fluidic devices ranging in characteristic sizes from a few microns to a few millimeters, and for the integration of electrical conductors and resistors into a single monolithic device. These elements can be assembled as individual devices and interfaced externally or installed readily in a three dimensional structure.

Ceramic tapes have a distinct advantage over silicon and glass in that minute structures, with minimum features in the size range from 10 microns to several thousand microns are easily fabricated. This is feasible because in the pre-fired (green) state, ceramic tapes are soft, pliable, and easily dissolved and abraded. Individual layers can be machined separately, stacked, aligned, and co-fired. Once a layered ceramic tape structure is fired, it becomes a tough and highly rigid body. Many layers of ceramic tapes, up to about 80 layers, can be bonded together to form complex three-dimensional structures. Electrically conducting paths can be built into these structures, and the incorporation of different materials into these substrates can be easily achieved.

Ceramic tape thus provides a convenient, and flexible medium for the fabrication and encapsulation of the various components described above for a variety of applications.

In addition to their versatility in fabrication and design, ceramic tapes offer many desired physical properties. Ceramic tapes can bond at relatively low temperatures, yet offer

a relatively high thermal conductivity, comparable to that of glass. Green tape devices can withstand higher usage temperatures than comparable devices made from other media. Green ceramic tapes can be more easily connected to a sample introduction device than analogous materials. Also, sub-components such as optics, silicon or metal windows, can also be conveniently integrated into channels or layers within the ceramic tape structure.

According to one aspect, the present invention provides a ceramic tape-based device that comprises metallic and polymer materials and incorporates active, moving structural elements that function as electromagnetic actuators. Electromagnetic force is used for activation. In recent years, electromagnetic actuators have gained popularity over electrostatically driven actuators for micro and meso-scale applications. A electromagnetic field can be induced by passing current through electromagnetic coils made out of conductor paste and fabricated onto individual layers of ceramic, green-state tapes. Structures which comprise one or more layers of ceramic tape containing such coils can be made which gather, focus, and then harness electromagnetic forces to create motion.

The electromagnetic actuation device of the invention comprises a flexible member which is adapted to be supported by one part thereof and to be deflected at a second part upon actuation, with multiple ceramic layers constituting the body of the device. A first ceramic layer supports the one part of the flexible member. A second ceramic layer comprises at least one electromagnetic coil and at least one contact member for

effecting current flow through the coil. The coil of the second layer is positioned adjacent the flexible member. At least the second part of the flexible member has magnetic properties so as to be deflected upon current flow through the coil. The actuation device may optionally include at least one other ceramic layer comprising at least one electromagnetic coil and at least one contact member to effect current flow through each electromagnetic coil of the other ceramic layer(s). It is preferred that the coil of any other ceramic layer(s) be substantially coextensive with the coil of the second layer. The contact members are operable to activate the device by the flow of current through the electromagnetic coils, thereby effecting actuation of the flexible member.

The ceramic tape-based electromagnetic actuators described herein are capable of producing magnetic fields up to tens of Gauss, and motions up to a few millimeters. Coils on different layers can be interconnected by conductor-paste filled vias or channels. Such actuators can be used for switches, valves, motors, stirrers and pumps in a meso-scale mechanical and fluidic components system or chip.

According to another aspect, the present invention provides transducers and sensors fabricated of ceramic tape. These devices respond to a physical stimulus such as temperature, light, sound, pressure, motion, humidity, flow, or the like and produce a corresponding electrical signal. For example, one embodiment of the present invention is a meso-scale pressure transducer fabricated from ceramic tapes. Pressure transducers can be utilized in a wide variety of applications and industries

such as industrial instrumentation, pumps, compressors, pressure control systems, and automotive control systems. The pressure transducers of the present invention are in the meso-scale range, and can be fabricated as small as 8μm in diameter with an internal cavity of 2μm. Because they are based on a ceramic tape substrate, they are capable of being subjected to higher pressure and temperatures relative to analogous silicon devices known in the art. For example, a pressure transducer fabricated from ceramic tape will have enhanced properties for operations above 150°C.

All parts for the transducer can be machined from green ceramic tapes utilizing either a computer numerically controlled (CNC) milling machine, or an isotropic etching technique involving the removal of the glassy binder of a partially sintered tape. This chemical exfoliation technique may be employed to separate the green ceramic tape into three layers, the middle layer being highly elastic, isotropic and homogeneous. The middle layer is then chemically thinned to achieve membrane like characteristics, with a thickness as small as about 50μm.

According to yet another aspect, the present invention provides an electromagnetically actuated, hybrid, meso-scale valve based on ceramic tape technology. These devices offer the advantage of shorter response time, lower power consumption, lower inactive volume and good dynamic characteristics. Analogous silicon micro-machined valves, by comparison, suffer from clogging or blockage due to moving parts within the micro valves.

The meso-scale valve of the invention has a body member which comprises at least first and second ceramic layers that define a flow channel, with an inlet port and an outlet port for transporting fluid through said flow channel, and a valve opening positioned in the flow channel between the inlet port and outlet port. The valve also includes a flexible diaphragm member which has a flexed condition engaging the valve opening and an unflexed condition disengaging the valve opening. Engagement of the valve opening by the flexible diaphragm member interrupts fluid transport through the flow channel. The valve further includes a base member comprising at least one other ceramic layer having at least one electromagnetic coil and a magnet mounted on the flexible diaphragm member to provide a magnetic force that causes the diaphragm to assume the flexed condition upon current flow through the electromagnetic coil.

According to still another aspect, the present invention provides meso-scale, electromagnetic, reciprocating diaphragm pumps fabricated from ceramic tapes and polymer films. The meso-scale pump of the invention has an inlet, an outlet, a pump cavity with first and second check valves, which control the opening of the inlet and outlet, respectively, and at least one flexible diaphragm adapted to be reciprocated to deflect into the cavity. The pump cavity is formed in a first ceramic layer, with at least one flexible diaphragm member being supported on the first ceramic layer overlying the cavity, and comprising at least one electromagnetic coil. A magnet is positioned in relation to the at least one flexible diaphragm member to provide a magnetic force effecting reciprocation of such member(s) upon current flow

through the coil. The valves operate to permit fluid flow through the cavity upon reciprocation of the flexible member(s).

In one pump design, a chamber, which is machined in ceramic tape substrate layers, is covered on one side with a polymer film diaphragm on which copper coils are formed. The diaphragm is electromagnetically actuated by the magnetic field of a permanent magnet. Flap valves, also made of polymer film, serve to control fluid flow into and out of the chamber. In another design, the chamber is covered on both sides with polymer film diaphragms, with coils formed on both diaphragms. Current is caused to be transmitted through these coils in opposite directions, also by the magnetic field of a permanent magnet.

Brief Description of the Drawings

The foregoing summary, as well as the following detailed description of the preferred embodiments, is better understood when read in conjunction with the appended drawings, in which:

Figure 1a is an isometric view of individual layers of ceramic tape prior to stacking, lamination and sintering.

Figure 1b is a cross-sectional view of the assembled and post-fired ceramic tape structure taken at line A-A depicted in Figure 1a.

Figure 2a is a plan view of three layers of green or unfired ceramic tape that together comprise a ceramic tape electromagnetic actuator.

Figure 2b is a plan view of the three layers of green or unfired ceramic tape which illustrate the electromagnetic

coils within the ceramic tape electromagnetic actuator of Figure 2a.

Figure 3a is a cross-sectional view of a ceramic-tape based actuator which includes a Kapton beam.

Figure 3b is a cross-sectional view of the experimental setup of a permanent magnet actuator which includes a Kapton beam.

Figure 3c shows the tip deflection of the Kapton cantilever beam as a function of coil current.

Figure 4a is a cross-sectional view of a ceramic-tape based actuator which includes a permalloy beam.

Figure 4b is a cross-sectional view of the experimental setup of a permanent magnet actuator which includes a permalloy beam.

Figure 4c shows the tip deflection of the permalloy cantilever beam as a function of coil current.

Figure 4d is an exploded, perspective view of the actuator device of Figure 4a, further including an underlying permalloy layer.

Figure 5 shows the exfoliation process for a partially sintered ceramic tape layer.

Figure 6a is a plan view of a ceramic tape-based pressure transducer.

Figure 6b is a cross-sectional view of the pressure transducer of Figure 6a.

Figure 7 shows the response of the ceramic tape transducer over time in comparison to the response of a silicon transducer.

Figure 8 is a cross-sectional view of a hybrid meso-scale valve.

Figure 9 depicts the various steps of the fabrication process for the flexible diaphragm of the valve of Figure 8.

Figure 10 is a plan view of the actuating coil geometry and a cross-sectional view of the layer interconnection for a five layer valve device.

Figure 11 is an exploded perspective view of a one diaphragm, meso-scale electromagnetic pump, in accordance with the present invention.

Figure 12 is an exploded perspective view of a two diaphragm, meso-scale electromagnetic pump, in accordance with the present invention.

Figure 13a is a plan view of two machined layers of LTCC tape and a polymer film diagram that together comprise a meso-scale electromagnetic reciprocating diaphragm pump in accordance with the present invention. The diaphragm layer is shown with and without check valves associated with the inlet and outlet ports in the ceramic tape layer.

Figure 13b is a cross-sectional view of the three layers of Figure 13a, laminated and co-fired in a monolithic three-dimensional structure, including passive valves.

Figure 14 illustrates the step-wise fabrication of the diaphragm component of the electromagnetic reciprocating diaphragm pump shown in Figures 13a and b.

Figure 15 is a graphical representation of the air-pumping flow rate (mL/min), as a function of actuation frequency (Hz) for the pump design shown in Figure 11.

Figures 16a and b provide a schematic illustration of the operation of the pump of Figure 11, with electromagnetically controlled valves.

Figure 17 shows the inclusion of a soft magnetic material in a cavity of a meso-scale structure built up from layers of co-fired ceramic tapes.

Detailed Description of Preferred Embodiments

Green ceramic tape is a versatile material that enables the combination of various electronic and meso-scale mechanical and fluid control elements into an integrated system within a monolithic structure, without the need for using external hydraulic interconnections. The term "minute" as used herein in reference to channels, passageways, conduits, vias, interconnections, cavities, chambers or other void spaces of the devices described below, is intended to signify at least one cross-section dimension of width or depth on the order of 10μm to 1cm, preferably on the order of 20μm to 500μm, and more preferably 50μm to 300μm. For many applications, channels of 200μm width will be useful. Cavities in the structures may have somewhat larger dimensions (e.g. 60μm to 1cm). The term "minute" and "meso-scale" are sometimes used interchangeably herein.

In fabricating the devices of the invention, ceramic tape layers are sized to meet the external dimensions of the intended device with the tape in its green or unfired state. Next, minute flow conduits, channels and/or portals are formed in the individual layers of tape. These flow conduits, channels or portals can be created in a variety of ways that include, but

are not limited to, mechanical machining (e.g., CNC milling and punching), chemical etching, laser machining, binder extraction, photo-forming or related techniques known in the art. A variety of shapes of flow conduits, including without limitation straight, T-shaped, U-shaped, L-shaped, spirals or curves, can be incorporated into one or more of these layers. Flow conduits in various layers are interconnected through the use of hollow vias. Alternatively, or in addition to the flow conduits, the layers may be printed with a pattern of metallic paths, conductors, thermistors, electrodes, electrical contacts, resistors, dielectric, or other electron conducting media, and co-fired. These layers are aligned, stacked, and then laminated together by sintering under tempertaure and pressure conditions sufficient to yeild a hardened, monolithic body, with complex internal interconnections. As another alternative, the aforementioned electronic components can be vapor deposited onto post-fired tapes. Tape composition may vary from layer to layer depending upon the desired properties and applications of a particular device or system.

One of the difficulties encountered in applying ceramic tape technology is the occurrence of dimensional changes, such as shrinkage, bowing and other related deformations, that occur during the lamination and sintering process. Deformation usually occurs in the direction perpendicular to the tape's x-y plane and the degree of shrinkage can be up to 15% of the tape's original dimensions. The degree of shrinkage on the external dimensions can be corrected by accounting for the shrinkage in the design process. It is more difficult, however, to correct the

dimensional changes such as shrinkage and bowing for the internal cavities or flow conduits. To remedy this, the internal cavities or flow conduits of the device are filled with sacrificial material, such as graphite and an organic binder mixture, prior to the lamination and sintering process. The sacrificial material then burns out during the sintering process and a hardened, monolithic device with a reduced amount of shrinkage on the internal conduits or cavities is produced.

In the fired state, small structures can be subsequently machined using diamond tools and lasers. Diamond points are used to create intricate features with small dimensions, and diamond slurry can be used to define symmetrical shapes. Both CO_2 and eximer lasers may be utilized to machine alumina and other ceramics with high precision.

Interconnects to an external flow supply can be added to the ceramic device through applying an adhesive, such as epoxy, to affix glass or metal fittings to the surface of the ceramic. If desired, glass fittings such as Kimble's Borosilicate Glass (KIMAX Brand N-51A) can be directly bonded to the ceramic by heating the glass above its transition temperature because the thermal expansion coefficient closely matches that of ceramic tape. Furthermore, metallic fittings can be bonded by metallizing the surface of the ceramic device and brazing the fittings to the ceramic surface.

The devices disclosed herein and the flow conduits within them are adaptable to a variety of design requirements depending upon the application. Design adaptions will include, for example, the formation of conduits of various shapes,

insertion of electrodes, resistors, thermistors and conductors, surface modifications, and the like. An example of a surface modification may be the application of an impervious coating to the internal cavities to reduce surface roughness and ease the passage of fluid through these cavities.

Because of their versatility, the devices of the present invention can be readily adapted to create meso-scale devices or systems that may include, but are not limited to, the following: electromagnetic actuators; reaction chambers; flow rate sensors; valves; integrated heat exchangers; flow conduits; thermistors; pumps, such as electromagnetic pumps or peristaltic pumps, stirrers, or heat pipes. The flexibility of the manufacturing method allows devices of other materials such as silicon or metal windows to be incorporated or embedded into the ceramic structure.

In preferred embodiments, the individual layers of the meso-scale devices comprise DuPont® 951 series Green Tape™. This tape is a low temperature co-fire ceramic ("LTCC") tape which consists primarily of alumina particles, glass frit, and organic binder. The tape is characterized by high strength, low coefficient of thermal expansion, refire stability, and is compatible with co-fired conductors (such as conducting paste that is screen-printed to the green ceramic tape) and via fill compositions. The thickness of the tape used for the devices can vary anywhere from about 100μm to about 250μm. As those skilled in the art will appreciate, however, other ceramic tapes can be utilized in practicing this invention.

The shrinkage of DuPont® g51 Green Tape™ is on the order of 12.27%±0.3% in the x, y direction and 15%±0.5% in the z direction, according to the DuPont® Design Parameters and Considerations for Green Tape™, which are incorporated herein by reference. Shrinkage can be affected further by the number and size of cavities within the individual layers or the degree of metallization on each layer.

Figure 1a depicts 3 layers of green ceramic tape designated 1, 2, and 3. Layer 3 has two openings, 4 and 5, that are formed by CNC milling or punching. Layer 2 has an L-shaped conduit or flow channel 6 therein. Holes 4 and 5 and flow channel 6 are formed by placing layer 1 and layer 2, respectively, onto the platform of a CNC milling machine. The green layers are held in place by a vacuum chuck or similar means. The CNC milling machine cuts openings 4 and 5 or flow channel 6 in accordance with a computer generated design for each individual layer of the device. Openings 4 and 5 and flow channel 6 are filled with a mixture of graphite and organic binder to maintain dimensional integrity of these internal cavities during the lamination and sintering steps. The graphite and organic binder mixture burns out during the sintering process.

Lamination and sintering can occur in a variety of ways and at different time, temperature, and pressure settings depending upon the ceramic tape used for the device, the number of layers, and any devices or pastes that are applied to the individual layers pre-firing. The aligned and stacked layers are subjected to temperature and pressure parameters sufficient to

bond the layers together into a unitary structure. Uniaxial lamination takes place in a hydraulic press with heated platens. The aligned, layer stack is pressed at about 70°C and 3000 psi for about 10 minutes to form a laminate. DuPont, the manufacturer of the 951 series tape, recommends that the laminate be typically rotated 180° after the first five (5) minutes. Alternatively, isostatic lamination occurs in a specially designed press which uses heated water or other fluid. Time and temperature are usually the same as uniaxial pressing but rotation of the laminate is not required. The laminate is vacuum sealed within a plastic bag to prevent water from attacking the ceramic tape layers.

After lamination is complete, the laminate is then fired on a setter tile within a kiln or furnace. The graphite and organic mixture and other organics within the laminate burnout at temperatures which range from about 200°C to about 500°C. The laminate is usually "soaked" within this temperature range to ensure full decomposition of the organics. The temperature is then gradually increased to the sintering temperature. Typical sintering temperatures for ceramic tape devices are between about 850°C to about 875°C. The device may be further subjected to additional firing steps if thick film resistors, dielectric, conductors, or other devices are applied in a post-fire operation.

Layers 1, 2, and 3 are aligned and stacked together to form a monolithic structure or device, 7 as shown in Figure 1b. Each layer is placed into a precision lamination fixture and positioned over tooling pins until all layers of the device 7 are

assembled. Figure 1b is a cross-sectional view of the ceramic tape structure after stacking, lamination and sintering taken at line A-A depicted in Figure 1a. Opening 4 can be used as an inlet port of the device 7 and flow channel 6 can be used as a capillary or fluid sample holder depending upon the desired application of device 7. Fittings can be affixed to opening 4 to facilitate introduction of fluid into flow channel 6. Opening 5 (not shown in Figure 1b) can be used as an outlet port of device 7 and can also have a fitting attached to it to facilitate fluid removal from the device.

The device 7 may be subjected to post-firing machining depending upon the desired application and design parameters. Machining methods vary depending upon considerations of cost, edge control, tolerances, and shape. A dicing saw may be used to form rectangular sharped devices with tight outside dimensional tolerances and high quality edges. Another machining method, ultrasonic cutting, allows tight tolerances and exceptional edge quality of unusually shaped parts. The drawback to ultrasonic cutting is that it is expensive and slow in comparison with other cutting methods. Yet another machining method, laser cutting, allows for tight tolerances at a lower price than comparable methods. However, the quality of the edges produced by laser cutting is poor. In comparison with post-firing laser cutting, pre-firing laser cutting of green ceramic tape will produce quality edges. Unfortunately, the outside edge tolerances of pre-fired laser machine parts are poor due to dimensional changes resulting from firing.

As previously noted, hybrid devices can be fashioned from LTCC tapes in conjunction with various other structural materials. Hybrid structures for high temperature applications may incorporate glass compositions, silicon or metals, so long as the thermal expansion coefficient of the selected material is compatible with the ceramic material. Once the ceramic is fired, a wide variety of plastic materials may be included in the resulting monolithic structure. Exfoliated, partially sintered LTCC tape may be used as a diaphragm material in the various devices described herein.

The fabrication methods described herein enable rapid prototyping, layered manufacturing with its attendant advantages and economical production of various minute, mechanical, fluid control and electronic devices and systems.

The following examples are provided to describe the invention in further detail. These examples are provided for illustrative purposes only, and should in no way be construed as limiting the invention.

EXAMPLE I: ELECTROMAGNETIC ACTUATORS

Figure 2a depicts the three major fabrication steps of electromagnetic actuators made using ceramic tape in accordance with this invention. Three layers of stamped-out 275mm thick DuPont 951 ceramic tapes with registration holes were used in the actuators of the current example. The top layer 10 supports the beam in space. The middle 11 and bottom 12 layers are substrates for the electromagnetic coils. The coils can be either screen-printed in the required pattern or CNC milled to a desired

pattern after depositing a layer of the conducting paste on the entire surface of the tape. In the present example, a CNC machine was used to cut a large square open space 13 in the top layer 10 and vias or small openings 14 on layers 11 and 12.

Figure 2b is a top view which illustrates the coil structure of a 3 layer actuation device. Silver Du Pont 6142D conductive paste was deposited on top of the bottom two layers 11 and 12. Vias 14 were also filled with silver Du Pont 6141 conductor paste. Coils 15 were milled by a CNC milling machine. An end-milling cutter with a 125μm radius was used to pattern each layer of the ceramic tape as needed. To allow connection with a power source, contact pads 16 composed of Du Pont 6146 conductor paste were printed on the coil ends. Electrical wires from the power source were soldered directly onto these contact pads. The conductor line thickness and the spacing between the lines were both 200μm after firing. The coil depicted in Figure 2b has 7 windings. The electrical resistance of the two-layered coils was 1.2Ω. The force experienced by the magnet in the vertical direction due to the magnetic field is determined by

$$F_z = M_z \int_v \frac{\partial B_z}{\partial z} dV, \qquad (1)$$

where F_z is the electromagnetic force in the vertical direction, M_z is the magnetization of the magnet, B_z is the z-component of the magnetic field due to the coils, and V is the volume of the magnet. B_z ($=\mu_o H_z$) induced by a single rectangular current loop

can be found in Wagner, B., Benecke, W., "Microfabricated Actuator With Moving Permanent Magnet," in *Proc. 1991 IEEE MEMS Conf.*, Nara, Japan, pp. 27-32, which is incorporated herein by reference. B_z induced by multiple loops can be found by adding B_z induced by each loop. In the above, it is assumed that B_z is not affected by the presence of the magnet.

After individual layers 10, 11, and 12 were machined, the three layers were aligned, laminated, and fired. A beam was bonded to the top layer. For a cantilever beam subjected to tip load, P, the tip deflection of the beam, w, is

$$w = \frac{PL^3}{3EI}, \qquad (2)$$

where L is the length of the beam, E is the Young's modulus of the beam material, and I is the moment of inertia. The electromagnetic force due to coil current ranging is influenced by the beam stiffness and magnet's weight.

In one actuator design depicted in Figure 3a, a flexible material such as Kapton™, which is a polyimide film, is used as the deflecting or cantilever beam 21. However, other material selections which are deformable in response to an electromagnetic force may also be used if desired. Kapton™ is preferred because it exhibits good mechanical, electrical, and thermal properties and is capable of withstanding temperatures up to about 400°C. The Young's modulus of Kapton™ was 2.5 gega-pascal ("GPa"). The thickness of the Kapton™ sheet used for the actuator can range from about 7.5μm to about 125μm. In the embodiment in Figure 3a, the Kapton™ beam used for the actuator

was 13mm long, 5mm wide, and 50mm thick. The Kapton™ and fired ceramic tape were laminated to form a monolithic device 20 by coating FEP (fluoropolymer resin) on the Kapton™. An Edmund Scientific NdFeB permanent magnet 22 with a 3.2mm diameter and 1.5mm thickness was bonded to the tip of the Kapton™ beam. Magnet 22 has a 1.2T magnetization and a 0.091 gram mass. As Figure 3a further illustrates, the two-layered square coils each of which are planar spirals with seven turns actuated the magnet. The present invention is not limited to the configuration depicted. It is anticipated that fabrication of larger number of coil turns in a small area would allow for larger beam deflection.

Figure 3b shows the experimental setup used to find the deflection of the tip of the Kapton™ beam due to electromagnetic actuation. A small amount of silver paste 23 was printed at the end of the Kapton™ beam 21 and a thin wire 24 of negligible weight and stiffness was connected to allow electrical connection with a multimeter 25. A probe station 26 was fixed on top of a Z-stage 27 that could traverse with 5μm precision. When the probe 26 made contact with the end of beam 21, an electric circuit closed, and the multimeter measured a finite resistance. The deflection of beam 21 relative to its initial undeflected state was found by comparing the location where beam 21 was first contacted to where it was first "lost". To measure the height of the beam's tip, probe 26 was slowly lowered until the circuit closed and millimeter 25 measured a signal. Subsequently, the probe 26 was elevated until the signal was lost and the circuit opened. The beam's deflection was determined as the probe's

position when loss of signal occurred. Typically, up to 100mm elevation difference was observed between the points of contact and loss of contact. This hysterisis phenomenon is partially attributed to electric contact resistance and partially due to the probe applying force on the beam when lowered.

The current to the electromagnetic coil was gradually increased in 0.2 A increments up to 1.4A. The measurement of the deflection of the beam tip was repeated at each current level. The whole experiment was repeated six times to find the scatter in the measurements. The results of these experiments are reflected in Figure 3c. As an additional measure of verification, a ruler was positioned behind magnet 22 and the deflection measurements were video taped. Figure 3c shows the results of both the probe measurements (shown as circles) and the video measurements (shown as 'x's'). As Figure 3c illustrates, a beam deflection exceeding one millimeter was obtained when the current was 200mA.

An alternative embodiment of the actuator of the present invention is depicted in Figure 4a. In Figure 4a, a permalloy or soft magnetic material beam 31, rather than a magnet-supporting Kapton™ beam was used for deflection. The permalloy selected, which was manufactured by Hamilton Precision Metals, Inc., had a saturation magnetization of about 0.78T and Young's modulus of about 230GPa. The composition of permalloy beam 31 was 80.21% Ni, 14.474% Fe, 4.33% Mo, 0.47% Mn, 0.31% Si, 0.20%C, 0.003% P, and 0.003%S. The dimensions of the permalloy beam used in the present example was 17mm long, 2.3mm wide, and

25μm thick. The permalloy enhances the intensity of the magnetic field generated.

Figure 4b shows the experimental setup used to test the permalloy beam actuator. The experimental setup is similar to that depicted in Figure 3b with the Kapton™ beam actuator. In the absence of an electromagnetic force, the gap between the beam's tip and the top coil was 1mm. The same coil design, namely a seven winding square coil configuration on two ceramic tape layers, was also used here. However, an additional permalloy sheet 33 was bonded to the bottom of actuator 30. This permalloy layer helped intensify the magnetic field generated by the coils.

Contact was made with the beam in the absence of magnetic forces. A certain amount of current was then applied to the coil. The resulting magnetic field caused beam 31 to deform. As a result of the deformation, the probe circuit was rendered open. The Z-stage 27 was slowly lowered until contact with the beam 31 was re-established. Due to contact resistance between the probe 26 and the beam 31, the probe had to be lowered beyond the equilibrium beam deflection state. The probe 26 was then elevated until the probe circuit became open. The location where the probe circuit was rendered open was the deflection of the beam end relative to the undeflected state. Coil current was then increased and deflection was measured using the same technique. The current was varied from 0A to 0.8A. The whole experiment was repeated four times to find the scatter of the measurements.

Figure 4c provides the results of this experiment which reflects the tip deflection of the permalloy beam 31 as a function of coil current. A comparison of the tip deflection of the permalloy beam 31 was made with and without the additional permalloy sheet 33 bonded to the base of the actuator. For example, the permalloy beam 31 with the permalloy sheet 33 bonded to the base of the actuator 30 deflected about 0.5mm at a current of 0.4A. In absence of the additional permalloy sheet 33, the beam tip deflected only about 0.2mm. The addition of permalloy sheet 33 decreases the repulsion of the permanent magnet 22 attached to the beam. The presence of the permalloy layer 33, therefore, enhances attraction and reduces repulsion. It is evident that the presence of a permalloy sheet layer 33 significantly increases the deflection of the beam. A permalloy sheet layer 33 can easily be added to the ceramic tape laminate in the fabrication process to obtain even larger deflections.

Alternative embodiments can have a flexible membrane that is attached on both ends rather than one end. These devices can be either one way or two way actuation devices or switches. Further embodiments of actuation devices can have a flexible membrane or beam above a cavity within the center of the magnetic coils, as illustrated in Figure 4d. The actuation device of Figure 4d is composed of three (3) ceramic layers 110, 11 and 112, with a Kapton beam 121 supported by the top layer 110. Vias 114 provide electrical connection between the electromagnetic coils 115. A permalloy base layer 117 serves to intensify the magnetic field produced by the device. This device can be

integrated with or incorporated into a monolithic package further comprising a pump and/or one or more valves as exemplified below.

EXAMPLE II: PRESSURE TRANSDUCERS OR SENSORS

Additional embodiments of the present invention include ceramic tape based pressure transducers. A pressure transducer is essentially a bridge circuit with two sides. The output produced by a transducer is voltage. One side of the circuit contains a resistor that acts as a reference. The other side of the transducer contains a resister which acts as a sensing element.

These devices are generally made in accordance with the aforementioned method. However, ceramic layers which function as the membranes of these devices can be prepared by chemical exfoliation, etching or other means, to a thickness of about 50μm to about 150μm, more preferably about 50 to about 100μm. As a result of chemical thinning, these layers become highly elastic, isotropic and homogenous. Exfoliated membranes from either sintered or partially sintered LTCC tapes facilitate the fabrication of ceramic pressure transducers operable in the temperature range up to at least 150°C and pressures in the range from atmospheric to one milli-Pascal.

The manufacturing process of a green ceramic tape, such as the DuPont 951 series ceramic tape, forces the ceramic tape to form anisotropic layers on its top and bottom. The middle or center layer of the green tape is more isotropic than the top and bottom surfaces. The middle layer of the green tape which is either partially or fully sintered can be isolated by

various chemical processes. Figure 5 shows the separation of an individual ceramic layers by the exfoliation process. The exfoliation process seems to obey Fick's Law for both partially sintered and sintered samples. That is, the reaction that occurs in the exfoliation process is diffusion controlled. In the case of a steady state reaction the diffusion length, L, that molecule of the exfoliating agent travels before interacting with the substrate is given by:

$$L = \sqrt{D\tau}$$

Figure 5 depicts the stages of exfoliation process at 85°C of a partially sintered tape. The layers of partially sintered samples actually peel away. Chemical exfoliation of sintered ceramic tape layers is not as effective as with partially sintered tape. If a sintered tape is used, the outer layers brush or chip away rather than peel. Preferably, hydrofluoric ("HF") acid, which is commonly used to etch silica, is used as the exfoliating agent to separate the layers.

In a preferred embodiment, a partially sintered individual layer of series 951 ceramic tape, Figure 5(a), is immersed in a hydrofluoric acid solution at a temperature range of about 85°C to about 95°C. The outer layers begin to separate from the middle layer, and ultimately peel away, as illustrated in Fig 5(b) and (c). The top and bottom layers removed are very thin and brittle; the remaining center layer, due to the

homogeneity of the particles, is uniform, elastic and suitable for use as a membrane within the pressure transducer.

The material removal rate and smoothness of the remaining layer is affected by various factors such as the concentration of HF acid, temperature of the solution, orientation of the sample in the solution, and type of firing process of the ceramic. It has been found that a concentration of 1:4 HF acid in a deionized water solution yielded the fastest and most desirable results. The temperature range of between 85°C and 95°C was most suitable for etching both partially sintered and sintered pieces. The etching rate at this temperature rate using a 1:4 HF acid-deionized water solution was found to be approximately 0.2 micrometers per minute. As in any thermally activated process, lowering the temperature caused the layer splitting to occur too slowly; the HF solution disintegrated all of the material before layers could be separated. Higher temperatures caused the reaction to occur too quickly, yielding a membrane with small and uneven thickness. A time of 20 to 25 minutes was found to be sufficient to exfoliate a partially sintered sample, and 30 to 35 minutes sufficed for a sintered sample. An additional factor which affected the exfoliation rate was whether the HF solution was reused. If the sample was soaked in fresh HF solution, this may begin to occur after about 15-18 minutes. If a previously used amount of HF is used again, the peeling may occur earlier, around 8 to 10 minutes. For this reason, it is believed that the residues of the exfoliation process catalyze the chemical reaction.

In general, the exfoliation process yields thin, elastic membranes of about 50 to 150μm in thickness. The 50 to 65μm membranes are difficult to manipulate. It has been found that 75 to 150μm membranes are suitable for use in a pressure transducer.

The ceramic tape can easily be used to construct three-dimensional forms using laminating and shaping techniques. In order to preserve the probable strength and temperature resistance of the remaining ceramic layers in the device, the joining method must be able to withstand the same or similar conditions as ceramic itself. Transducers fabricated from either fully-sintered to partially sintered, fully-sintered to fully-sintered, partially sintered to partially sintered can be joined by various bonding schemes such as glass frit and water or glass frit and an organic binder. In the preferred embodiment, two partially sintered pieces are joined together with a mixture of glass frit and organic binder and then sintered together. This arrangement seems most capable of preserving the temperature resistance of the material.

Figures 6a and b provide an illustration of a ceramic tape pressure transducer 35 in accordance with the present invention composed of an exfoliated partially sintered ceramic membrane 38 prepared as described above. The pressure of the transducer is measured as a function of the membrane deformation where two piezo-resistors are screen printed. Two piezo-resistors 37a and 37b were used to achieve temperature compensation. Using shrinkage matched paste, nominal thick film technology was used in the screen printing of the piezo--

resistors. The base of the transducer 39 was fabricated using several layers of LTCC tapes, which were laminated and fired. For testing purposes, a vacuum was drawn on the device, as indicated by the arrows in Figure 6b, by means of a vacuum pump.

The LTCC transducer was tested by comparing its response with that of a commercial silicon pressure sensor. The LTCC transducer was tested under temperatures in the range from 25 to 150°C, while the silicon-based sensor was kept at room temperature. The negative pressure applied to the transducer ranged from atmospheric to 100 Torr (one milli-Pascal). The testing set-up consists of a vacuum line which supplied negative pressure to the ceramic transducer. It lies on a vacuum chuck coupled through an o-ring, and adjacent to commercially available silicon piezo-resistive pressure transducer. An attached PC collects data on the measured change in voltage over time as the pressure is raised and lowered through a valve.

Figure 7 provides the results of the comparative testing. As Figure 7 shows, one can infer that the response time of the LTCC sensor is faster that the open-close time for the valves in the testing manifold (-0.27 seconds).

EXAMPLE III: MINUTE VALVE

An additional embodiment of the present invention includes meso-scale valves to be used in ceramic tape based integrated systems. These devices can be fabricated entirely of ceramic tape layers, or integrate other material layers forming a hybrid device. One such device 40, comprises, among other things, a multilayer coil 41, a fluidic system 42 comprising an

inlet port 43 and outlet port 44 and a flexible diaphragm 45, having a bonded magnet 46, constituting a media interface, as shown in Figure 8. Each subsystem can be manufactured separately then integrated into a unitary device. Device dimensions are in the meso or intermediate range with the smallest features such as the fluid conduit in the manifold of 400μm and the largest features, such as an actuating coil, of 15mm.

Figure 9 depicts the various steps of the fabrication process for a flexible diaphragm sub-system which can be integrated into the valve device. Flexible diaphragms, when used with a rare earth magnet, allows for electromagnetic actuation of the device. This subsystem can be formed according to the following steps: (a) thickness definition by diffusion, (b) aluminum mask deposition, (c) spring geometry definition, (d) silicon plasma etching to form vias, (e) cleaning and Si nitride deposition, (f) definition of area and RTV dispensing by employing photoresist layers, (g) backside anisotropic etching and diaphragm release, and (h) cleaning and magnet bonding. This design is implemented using silicon technology of the present art for a square spiral spring that is covered with an polysiloxane film.

An additional subsystem that can be independently assembled is an actuating coil. Figure 10 displays actuating coil geometry 52 and layer interconnection 54 of a fabricated device 55. The hybrid coil consists of several layers of planar spiral coils such as layers 50 and 51 in Figure 11. In a preferred embodiment, a square spiral coil of 1 x 1 cm^2 is designed to have a small quantity of interconnecting vias and

connected so as to preserve the magnetic field direction. A single layer was designed to have silver conductors of 80μm lines and 10μm thickness with 80μm space between lines, rendering a 20 turn single layer coil. The total coil resistance is high (120 Ohms). The coil resistance can be lowered by using tape machining techniques to obtain 60μm thickness. Due to coil high resistance, thermal consideration limits the current to 150 mA. Vias of 250μm were used to ensure layer interconnection. A five and eight layer coil have been fabricated using DuPont 951 Green Tape™ and the aforementioned method. The silver spiral coils or grooves can be machined into green tape or screen printed onto the tape.

The fluidic subsystem 47, including valve opening 48, was also fabricated at the same time using separate LTCC green tape layers.

These actuating coil and fluidic subsystems were combined with the anisotropically etched silicon rectangular planar spring and a high-energy product SmCo permanent magnet to form a hybrid device. The multilayer actuating coil and fluidic subsystem, are aligned, stacked, laminated and sintered together to form a LTCC substrate. The above-described flexible diaphragm is bonded to the LTCC substrate using a dispensed gasket of polysiloxane, which also serves to maintain the appropriate spacing between the center coil and magnet which is about 300μm. A polysiloxane valve seat 49, as shown in Figure 8, is also deposited onto the top layer, with a controlled dispenser to prevent valve leak. The hybrid device consists of 5 layers of planar spiral coils. The total coil resistance of the device

tested was 120 Ohms. A 200 micrometers deflection of the silicon $30\mu m$ thick rectangular planar spring with polysiloxane sealing was obtained using a 900 Gauss SmCo magnet ($1\mu m$ diam).

Alternative embodiments of the valves of the present invention may include valves which are normally in the open position or valves which are normally in the closed position. Yet other valves may have variable or partially open position operation due to a fluctuation in the current within the electromagnetic coil. The valve opening is tied to the fluctuation in electric current.

EXAMPLE IV: MINUTE ELECTROMAGNETIC PUMPS

Two separate embodiments of minute electromagnetic reciprocating diaphragm pumps were designed and fabricated using LTCC tapes and polyimide film. Figure 11 depicts schematically the major components of the first pump embodiment. Several layers of ceramic tapes were used to form the pump chamber 60. Two passive valves 66a and 66b were made out of Kapton™ polyimide film. The diaphragm 67, also made out of Kapton™, was bonded to the ceramic substrate 61 with epoxy. Glass tubes 63' and 64' were then bonded to the inlet port 63 and outlet port 64, respectively, to facilitate flow rate measurements and the introduction of back-pressure. The permanent magnet 69 can be placed either below the diaphragm 67 or above it, with appropriate spacers between the diaphragm and the magnet.

In the second design, two Kapton diaphragms 167 and 167' were used to cover the chamber 160 as shown in Figure 12. Rather than having one moving diaphragm, two diaphragms were

mounted on ceramic substrate 161 in order to increase the flow output. The inlet (not shown) and outlet 164 openings were machined directly in the Kapton film and the passive valves for the inlet 166a and outlet (not shown) openings were bonded adjacent to the openings. The two coils on each of the two diaphragms, formed as described below, were connected through a via in the ceramic layer in such a way that the currents in the coils flowed in opposite directions. Opposite current directions produced opposite forces on the diaphragms. Inlet and outlet tubes 163' and 164' were provided in fluid communication with the inlet and outlet, respectively. In this embodiment also, magnet 169 may be positioned above or below the diaphragms.

A. Fabrication Techniques

1. Pressure Chamber and Passive Valve Fabrication

Figure 13a depicts the fabrication of the pressure chamber and passive valves. In the first step, two (2) layers of LTCC 61 and 62 were laminated and machined to form a 2cm x 2cm x 500μm chamber. The 0.45mm diameter inlet 63 and outlet 64 openings were machined in a third layer. In the second step, all layers were laminated together and co-fired to form a single monolithic structure 65. In the third step, Excimer micromachining laser system was used to fabricate 13μm thick 0.7mm x 5mm rectangular Kapton passive flap valves 66a and 66b. The Kapton valves were placed over the inlet and outlet openings and bonded to the structure with epoxy.

2. Diaphragm Fabrication

Figure 14 shows the processing steps for the fabrication of electromagnetic coils on the copper-coated

Kapton™ diaphragm using photolithographic method. A 25mm x 25mm x 30μm thick Kapton™ film with 5μm thick copper coating (Gould Electronics) on both sides was used. The copper surfaces were cleaned with alcohol and DI water, and dried with air. In step 1, positive photoresist was spin-coated at approximately 4000 rpm for 25 seconds on one surface. It was then dried for 2 minutes at 115°C. The other copper surface was then spin-coated with positive photoresist and dried at 115°C for 2 minutes. A small indent was made at the center of the Kapton for top and bottom surface alignment during the UV light exposure. The indent was used to align the center of the coils. In step 2, the surfaces were exposed to UV light with a coil mask on top of the surface. The other side was exposed in such a way as to ensure that the current in both coils will flow in the same direction. This is important since opposite current directions would cancel the forces created by the two coils. In step 3, after UV exposure, an indent was punched through to form a via (170a and 170b in Figure 12) between the top and the bottom coils. In step 4, the photoresist was then developed leaving photoresist of coil-shape on top of the copper surfaces. The copper was then etched with copper etching solution. The chromium coating was etched with potassium permanganate/sodium hydroxide solution and oxalic acid solution. In step 5, the remaining photoresist was stripped with photoresist stripper. Next, the via was filled with copper paste. Electrical connections to the coils were then attached. The diaphragm contained 20 coils in an area of 2cm x 2cm. The width and the spacing of the coils were 200μm.

3. Bonding of the Components

After fabrication of the pressure chamber with passive valves and the diaphragm was completed, as described above, the pressure chamber and the electromagnetic coil-containing diaphragm were bonded to form the pump. A glass tube 63' was bonded to the inlet hole. Tygon tubing was connected to the glass tube. Epoxy was used for bonding. NdFeB magnet 69 of 1.26 x 0.66 x 0.39 inches (32mm x 16.76mm x 9.91mm, Edmund Scientific) was disposed below the diaphragm 67. Spacers were placed between the diaphragm and the magnet to allow room for the diaphragm's deflection. The distance between the magnet and the diaphragm was about 0.5mm.

The second pump embodiment was fabricated using the same methods, with two diaphragms, rather than one. The inlet and outlet ports on one Kapton diaphragm were machined with Excimer laser. Kapton flap valves were bonded over the openings.

B. Performance Testing

Testing was carried out to evaluate the first pump's performance. A function generator (Tektronix GFG250) was used to apply time-stepped signal to an amplifier. The amplifier was used to increase the magnitude of the power. Typically, 190 mA of RMS current was applied to the coils. The resistance of the two coils connected in series and mounted on the Kapton diaphragm was 45Ω. A water slug was introduced at the inlet of the Tygon tubing of 1/16 (1.59mm) diameter that was connected to the inlet port. The tube was vertical so that the water slug flowed against gravity. Once steady state conditions were achieved, the distance traveled by the slug during a 15 seconds period was

measured to obtain the flow rate. Each measurement was repeated six times.

By measuring the distance traveled by the water slug in the vertically clamped Tygon tubing, air-pumping flow rate was calculated for the first pump design. Figure 15 shows the flow rate as a function of actuation frequency. The vertical bars indicate the scatter of the data. The circle represents the average of six measurements. As the actuating frequency increased, the flow rate increased, attained a maximum, and then decreased. The maximum airflow rate was about 1.7 mL/min at 50 Hz.

The results obtained were not as good as would be expected if the pump's design and operation conditions had been optimized, which was not the case in this test. These preliminary results show, however, that the hybrid pumping devices of this invention are viable components for use in meso-scale chemical and biological analysis systems, the so-called "lab-on-a-chip". Several design factors can be improved to enhance performance of the pumps, such as using thinner Kapton diaphragms to achieve larger deflections, using better size and placement of the permanent magnet to achieve larger forces, using electromagnetically actuated valves to reduce leakage, and the optimizing of coil dimensions to reduce stiffness of the diaphragm.

The operation of the first pump embodiment is illustrated schematically in Figure 16. Figure 16a shows the charge cycle, in which the interactions between the electromagnetic coils 70 formed on diaphragm 71 and magnet 73

attract the diaphragm toward the magnet; and Figure 16b shows the discharge cycle in which magnetic force repels the diaphragm 71 from magnet 73. The direction of fluid flow in each cycle is indicated by the arrows. Figure 16 also shows an alternative for controlling operation of the inlet and exit port valves of the pump chamber. As depicted in Figure 16, electromagnetic coils 75a and 75b may be formed on each of the check valves. In this design, the same magnetic force that produces deformation of the diaphragm can be caused to open and close the check valves.

The principles employed in the two diaphragm pumps described immediately above may be adapted to the design of a peristaltic pump and/or stirrer. Thus, traveling waves with the same amplitude and frequency but opposite phase maybe transmitted in membranes and induce peristaltic motion in the fluid. The peristaltic pump/stirrers includes a fluid-filled cavity bounded from below and above by flexible membranes or diaphragms. By forming electrical conductors on these membranes and passing electrical currents through these conductors in the presence of a magnetic field, the membranes can be caused to vibrate with relatively large amplitudes and in a pre-determined way. Since the conductors can be shaped using photolithography, fairly complicated motions can be induced in this way. For example, by appropriate phasing of the current, one can induce traveling waves in the membrane, which, in turn, will cause peristaltic pumping in the fluid. The construction of membranes made out of Kapton having electromagnetic coils formed thereon, has already been described in detail.

The intensity of magnetic fields associated with the electromagnetic devices described herein may be increased by the inclusion in the devices of "soft" i.e. easily magnetized and demagnetized material. This can be accomplished, for example, by plating surfaces with such material, as shown in Figure 4d, by embedding soft magnetic material 81 in cavities 83 formed in the ceramic tapes 85, as shown in Figure 17, or by preparing ceramic tape formulations from magnetic oxides. Magnetic materials that are suitable for this purpose include, without limitation, ferrites magneto plumbites permalloy and the like.

While certain embodiments of the present invention have been described and/or exemplified above, various other embodiments will be apparent to those skilled in the art from the foregoing disclosure. The present invention is, therefore, not limited to the particular embodiments described and/or exemplified, but is capable of considerable variation and modification without departure from the scope of the appended claims.

What is claimed is:

1. An electromagnetic actuation device comprising:
   a. a flexible member adapted to be supported by one part and to be deflected at a second part upon actuation;
   b. a first ceramic layer supporting said one part of the flexible member; and
   c. a second ceramic layer comprising at least one electromagnetic coil and at least one contact member for effecting current flow through said electromagnetic coil, said coil being positioned adjacent said flexible member, at least the second part of said flexible member having magnetic properties so as to be deflected upon current flow through said coil, and, optionally,
   d. at least one other ceramic layer comprising at least one electromagnetic coil and at least one contact member to effect current flow through each electromagnetic coil of said at least one other ceramic layer, said contact members being operable to activate said device by the flow of current through said coils, thereby effecting actuation of said flexible member.

2. An electromagnetic actuation device according to claim 1, wherein said electromagnetic coil of said second ceramic layer is substantially co-extensive with said

electromagnetic coil of said at least one other ceramic layer.

3. An electromagnetic actuation device according to claim 1, wherein said flexible member comprises an elongated beam having a magnet at said second part.

4. A device according to claim 3, wherein said flexible member is non-magnetic.

5. An actuation device according to claim 1, wherein said flexible member is an elongated beam of soft magnetic material.

6. An electromagnetic actuation device according to claim 1, wherein at least one of said ceramic layers comprises multiple plies of low temperature co-fired ceramic tape.

7. A minute pump having an inlet, an outlet, a pump cavity with first and second check valves, which control the opening of said inlet and said outlet, respectively, and at least one flexible diaphragm adapted to be reciprocated to deflect into the cavity, said pump comprising:

   a. a first ceramic layer having said pump cavity therein; said at least one flexible diaphragm member being supported on said first ceramic layer overlying said cavity, and comprising at least one electromagnetic coil;

b. a magnet positioned in relation to said at least one flexible diaphragm member to provide a magnetic force effecting reciprocation of said member upon current flow through said coil; the valves operating to permit fluid flow through the cavity upon reciprocation of said flexible member.

8. A pump according to claim 7, wherein said check valves are passive valves.

9. A pump according to claim 7, wherein said check valve are electromagnetically operated.

10. A pump according to claim 7, including a second flexible member mounted on said first ceramic layer, said first and second flexible members being disposed on opposite sides of said cavity, each of said flexible members comprising an electromagnetic coil, said coils being interconnected to provide current flow in opposite directions to effect opposite forces on the flexible members.

11. A pump according to claim 10, wherein at least one of said flexible members constitutes the mount for said check valves.

12. A pump according to claim 7, including a second ceramic layer mounted on said first layer on the side opposite said

flexible member, said check valves being mounted on said second ceramic layer.

13. A pump according to claim 7, wherein said check valves comprise a polyimide film.

14. A pump according to claim 7, wherein said magnet is a permanent magnet having a pole face substantially coextensive with said electromagnetic coil.

15. A pump according to claim 7, wherein at least one of said ceramic layers comprises multiple plies of low temperature co-fired ceramic tape.

16. A pump according to claim 7, which further includes a mass of soft magnetic material which is effective to increase the intensity of said magnetic force.

17. A minute valve having a body member comprising at least first and second ceramic layers defining a flow channel, with an inlet port and an outlet port for transporting fluid through said flow channel, and a valve opening positioned in said flow channel between said inlet port and outlet port; a flexible diaphragm member having a flexed condition engaging said valve opening and an unflexed condition disengaging said valve opening, engagement of said valve opening by said flexible diaphragm member interrupting fluid transport through said flow channel; a

base member comprising at least one other ceramic layer having at least one electromagnetic coil; and a magnet mounted on said flexible diaphragm member to provide a magnetic force that causes said diaphragm to assume said flexed condition upon current flow through said electromagnetic coil.

18. A valve according to claim 17, having a base member comprising multiple ceramic layers with at least one electromagnetic coil disposed therein.

19. A valve according to claim 17, wherein said magnet is a permanent magnet which is mounted in registry with said valve opening.

20. A valve according to claim 17, wherein at least one of said ceramic layers comprises multiple plies of low temperature co-fired ceramic tape.

21. A valve according to claim 17, which further includes a mass of soft magnetic material which is effective to increase the intensity of said magnetic force.

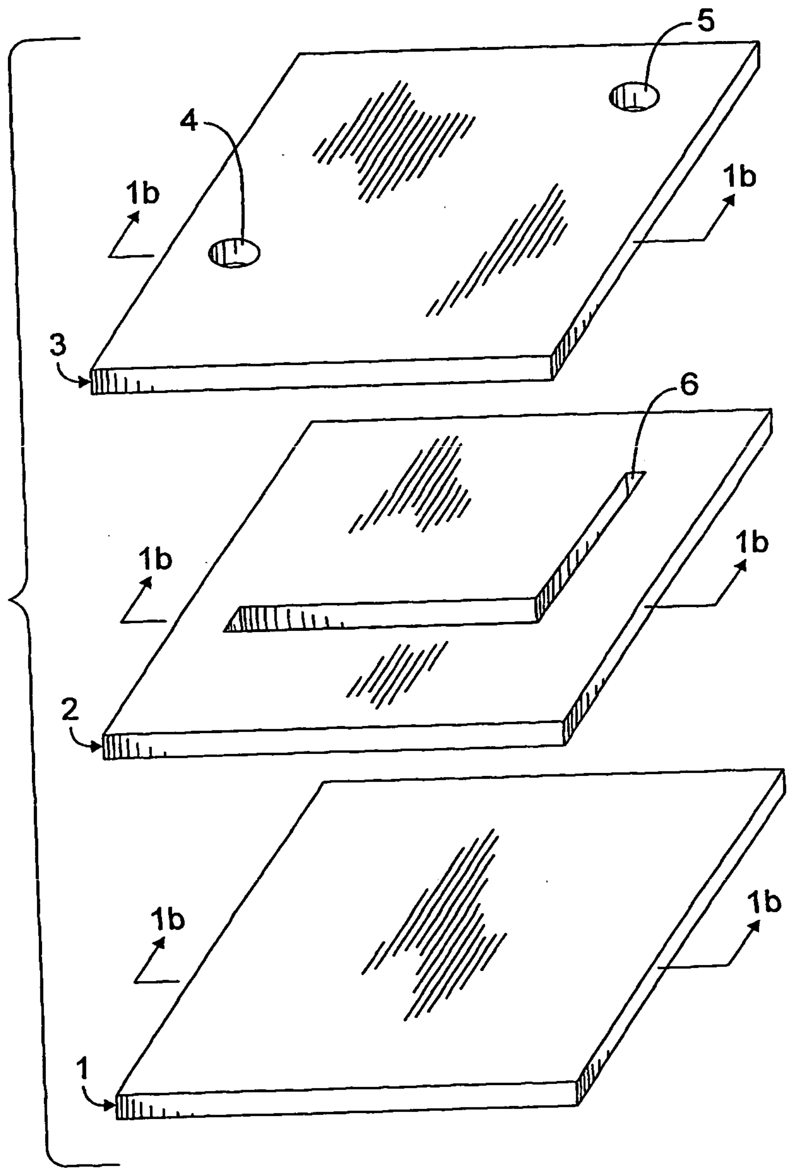


Fig. 1a

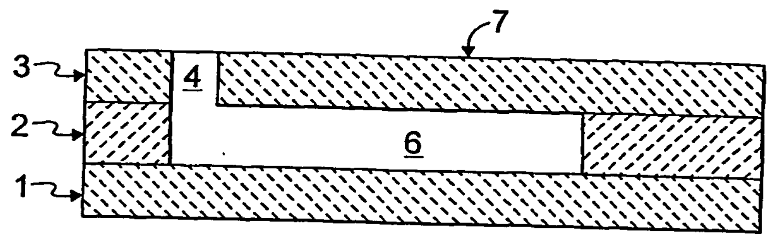


Fig. 1b

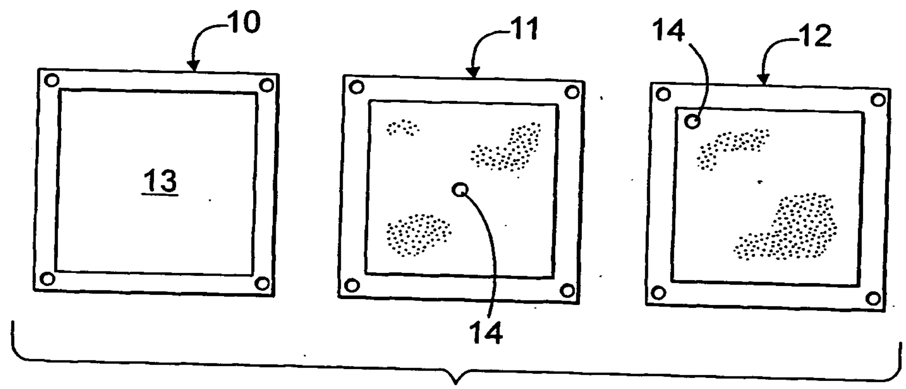


Fig. 2a

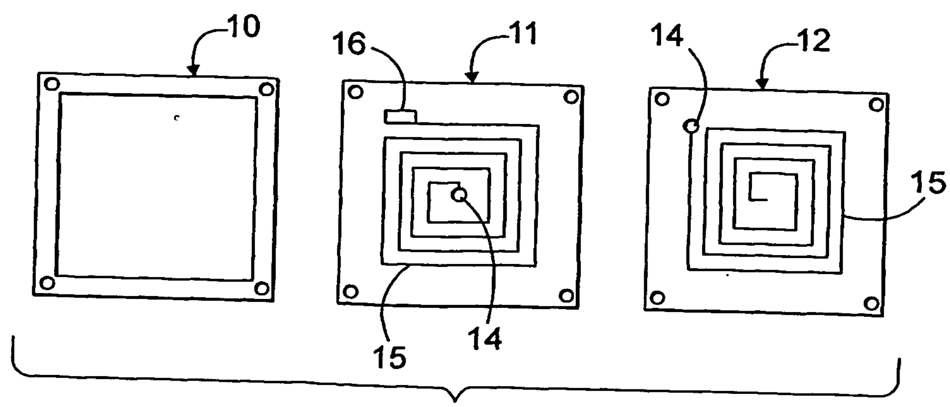


Fig. 2b

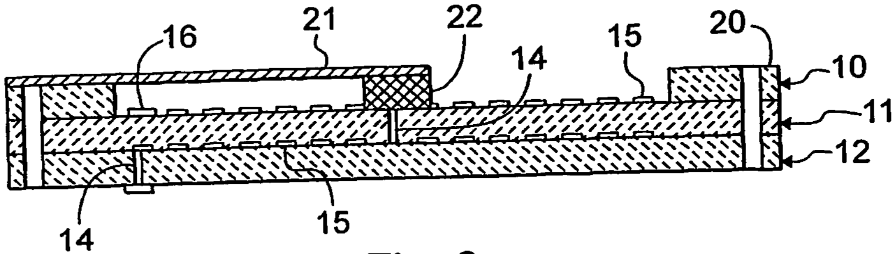


Fig. 3a

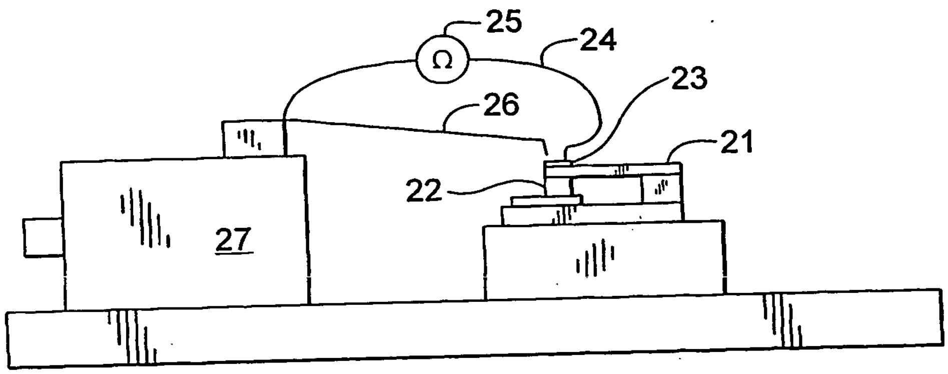


Fig. 3b

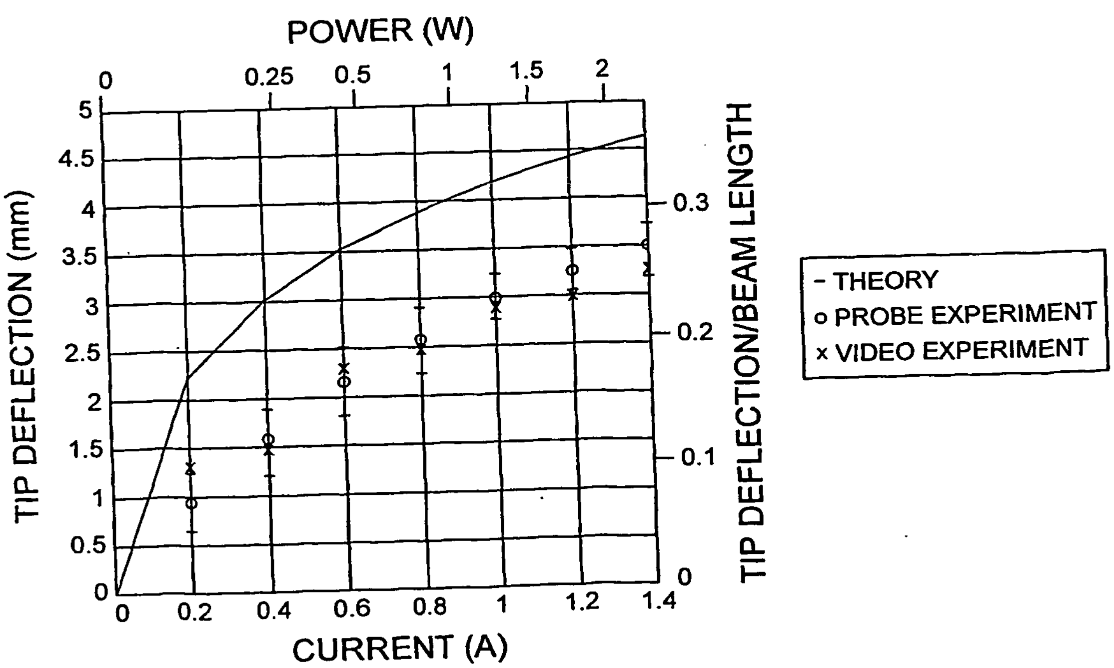


Fig. 3c

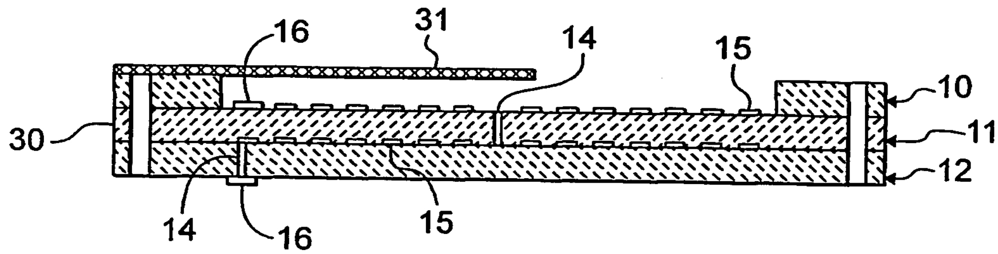


Fig. 4a

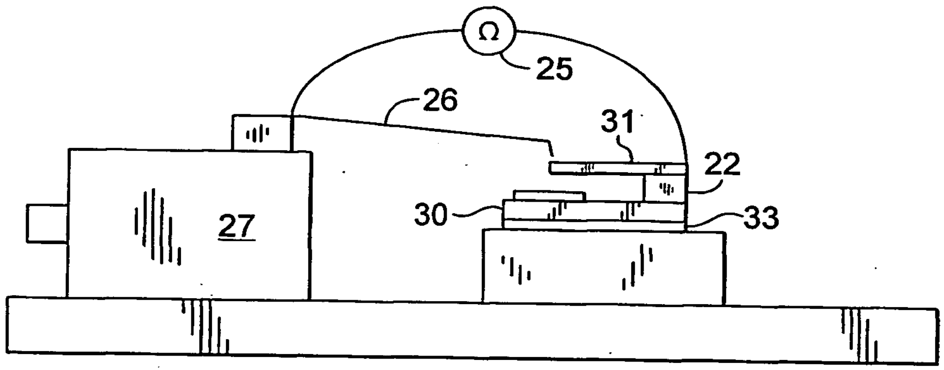


Fig. 4b

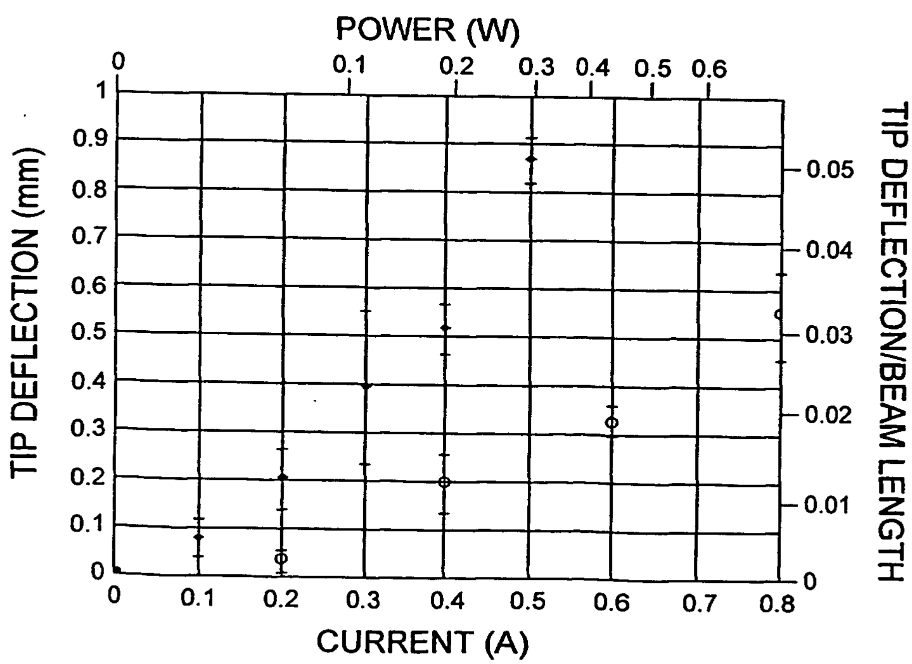


Fig. 4c

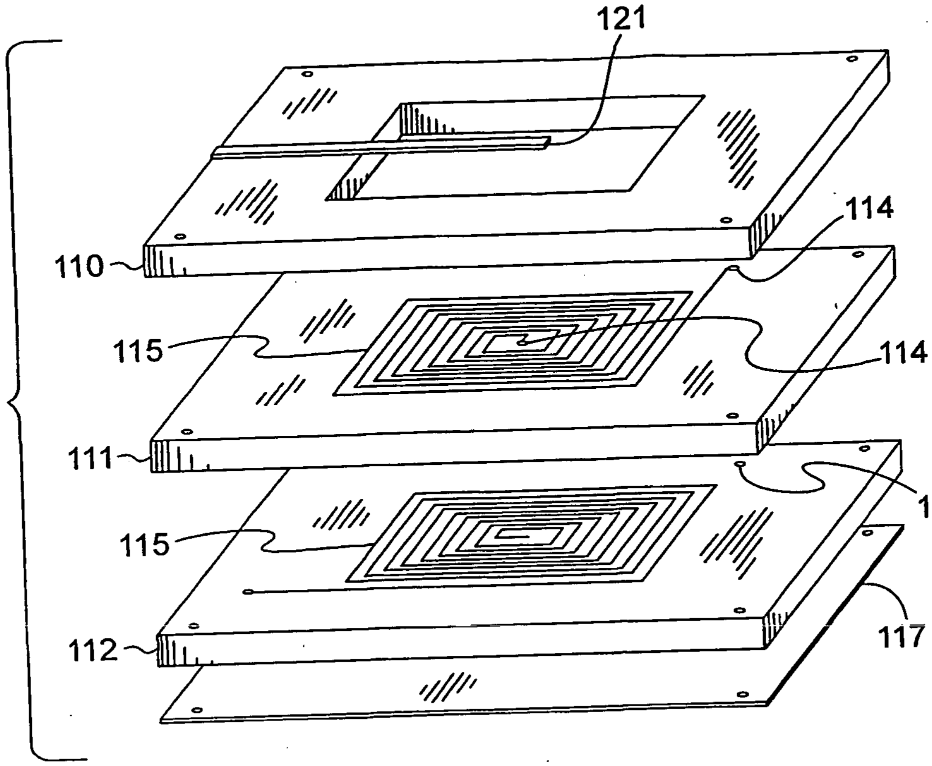


Fig. 4d

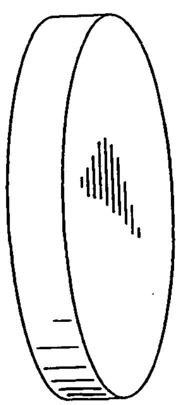


Fig. 5a

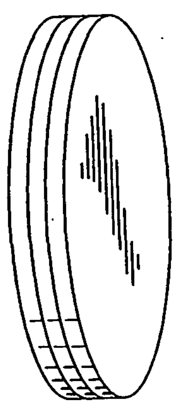


Fig. 5b

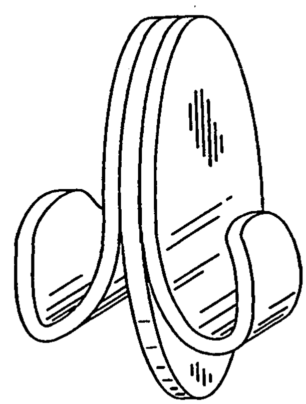


Fig. 5c

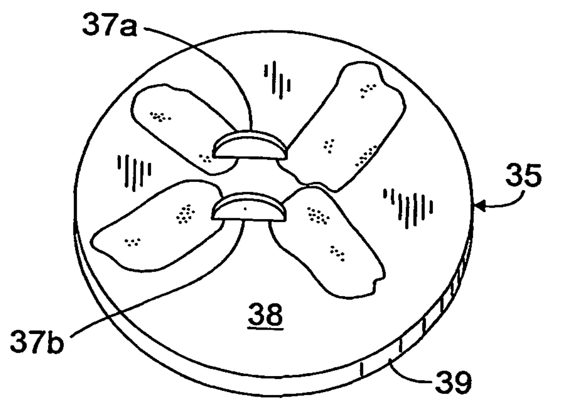


Fig. 6a

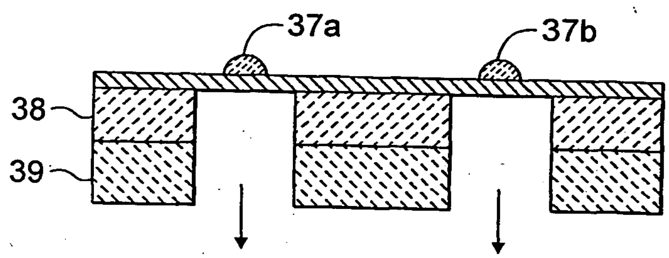


Fig. 6b

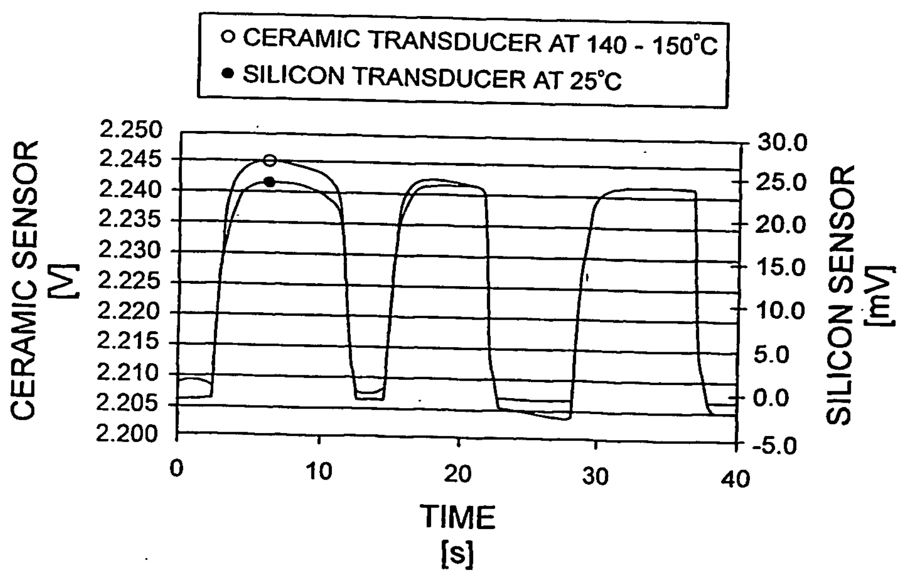


Fig. 7

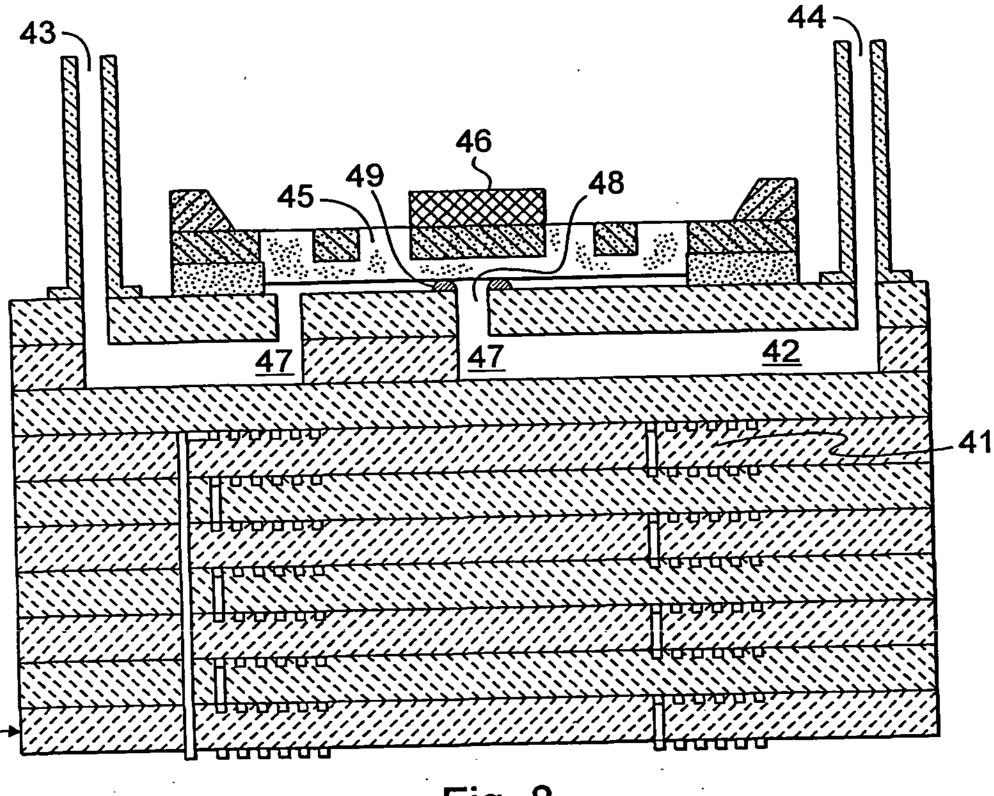


Fig. 8

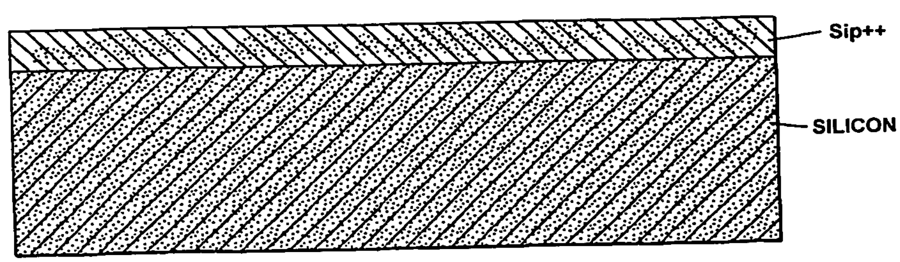


Fig. 9a

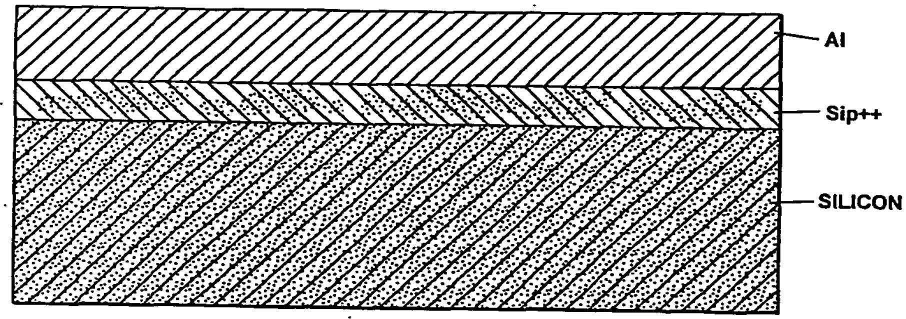


Fig. 9b

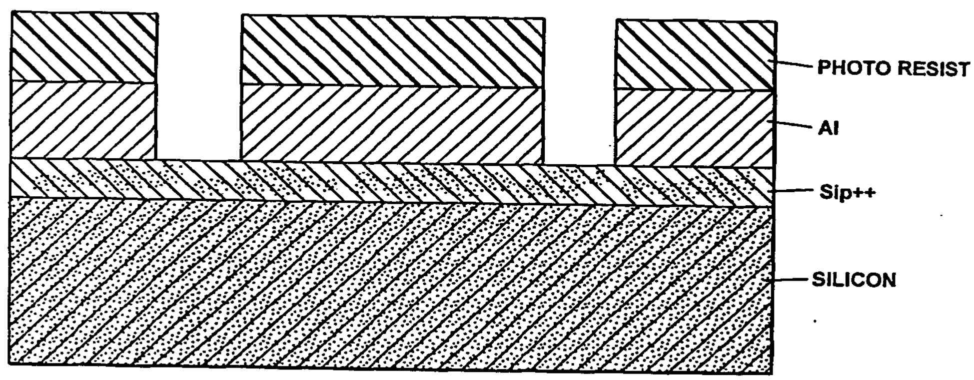


Fig. 9c

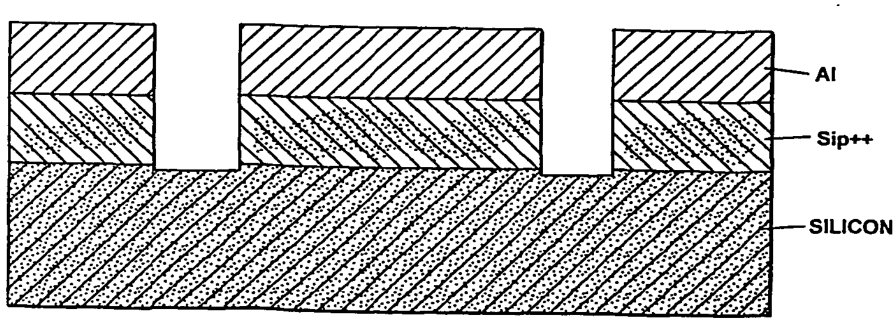


Fig. 9d

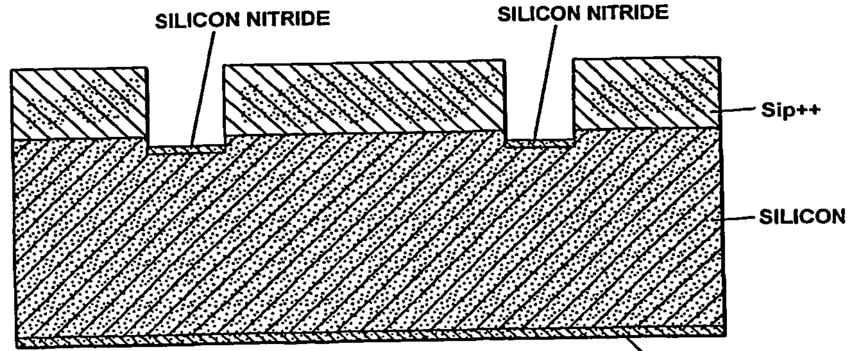


Fig. 9e

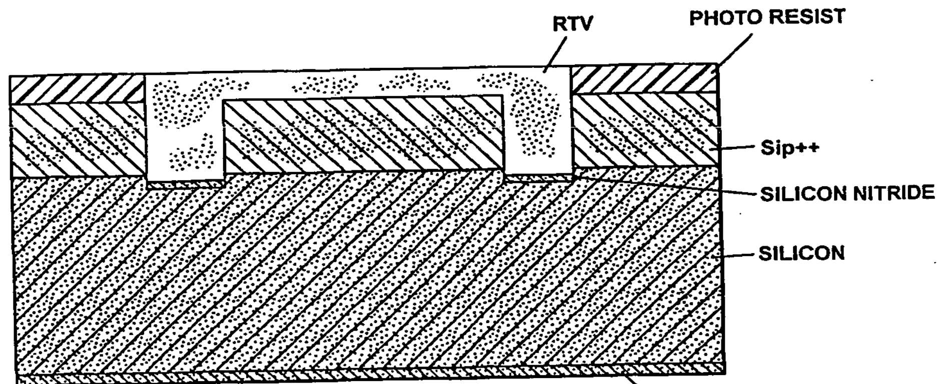


Fig. 9f

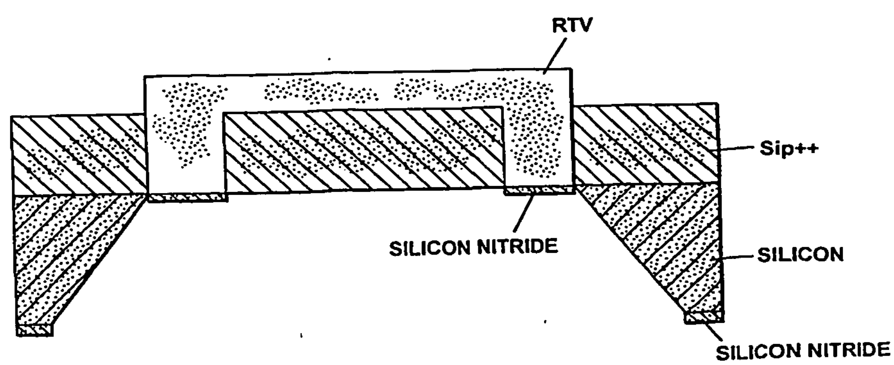


Fig. 9g

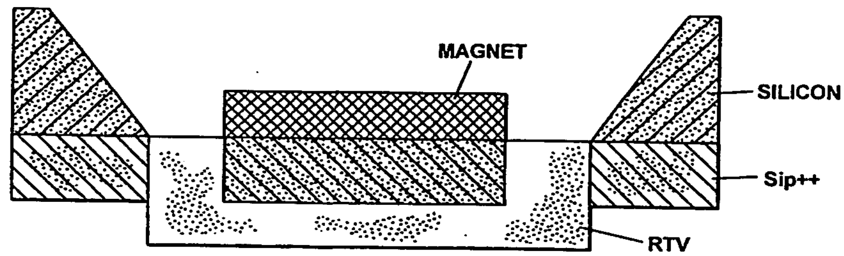


Fig. 9h

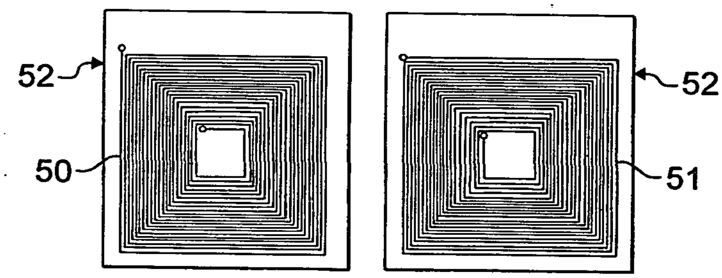


Fig. 10a

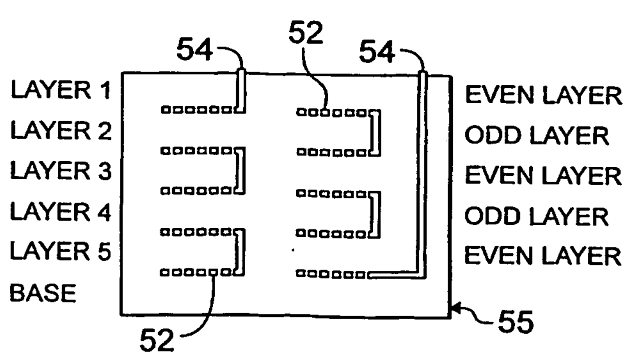


Fig. 10b

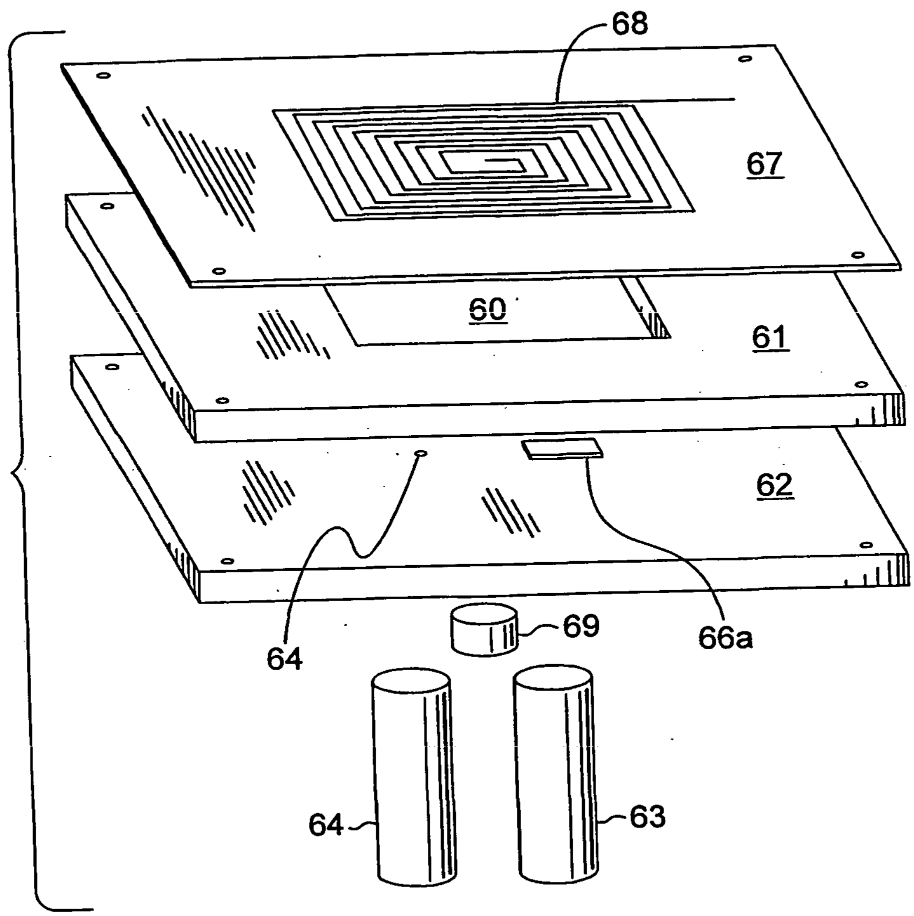


Fig. 11

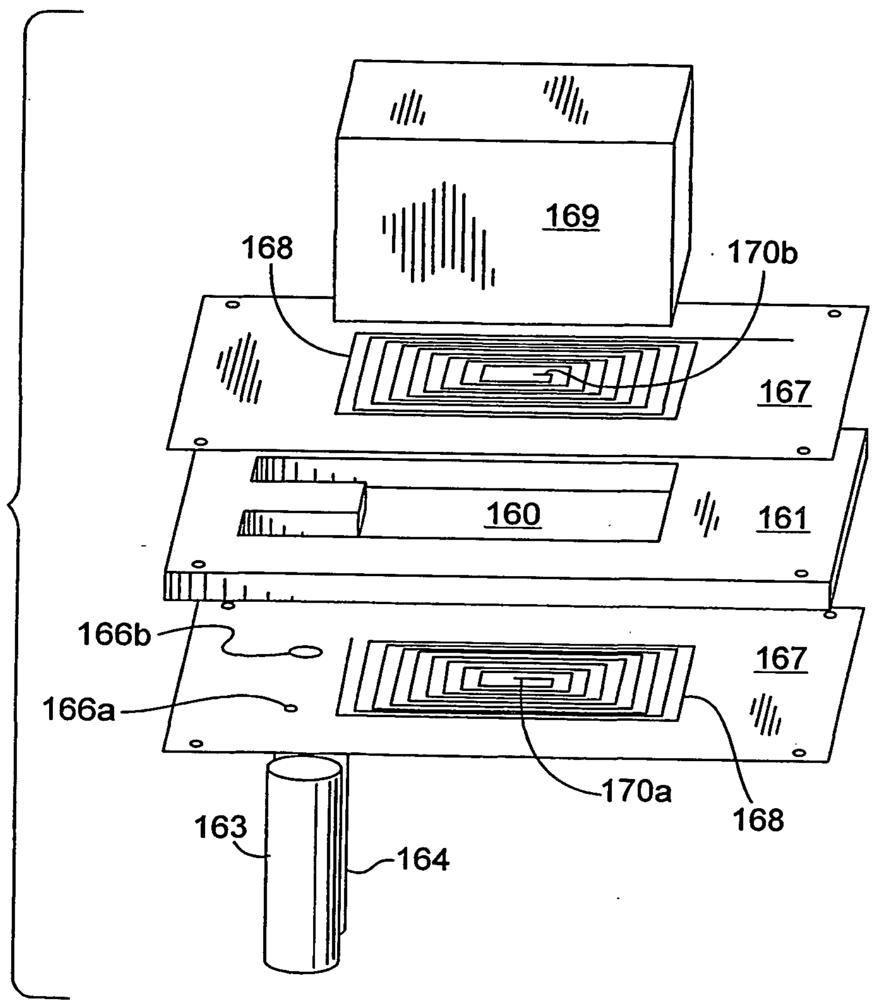


Fig. 12

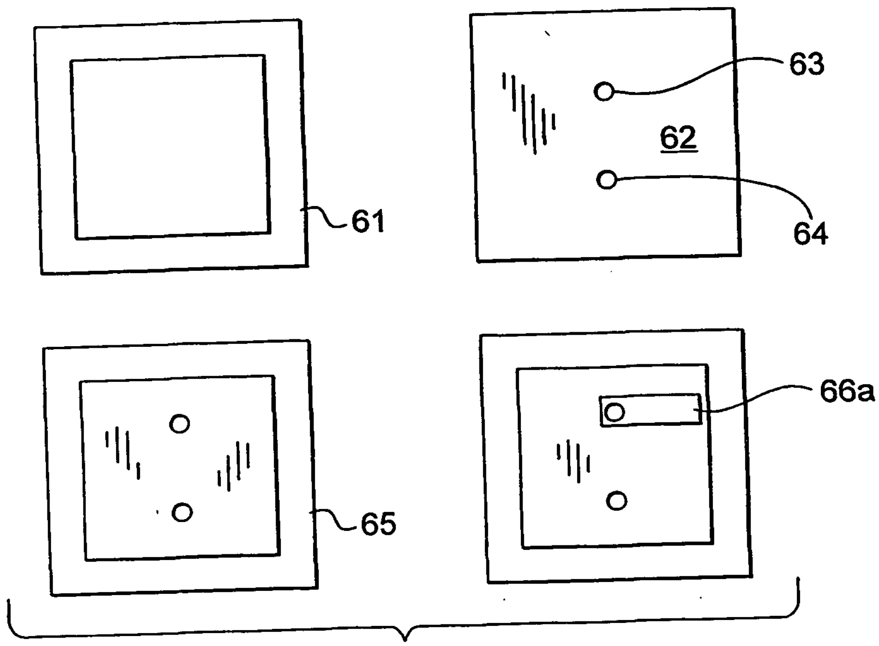


Fig. 13a

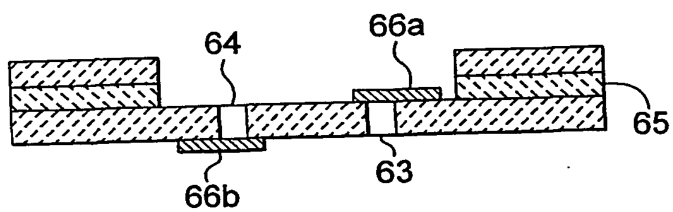


Fig. 13b

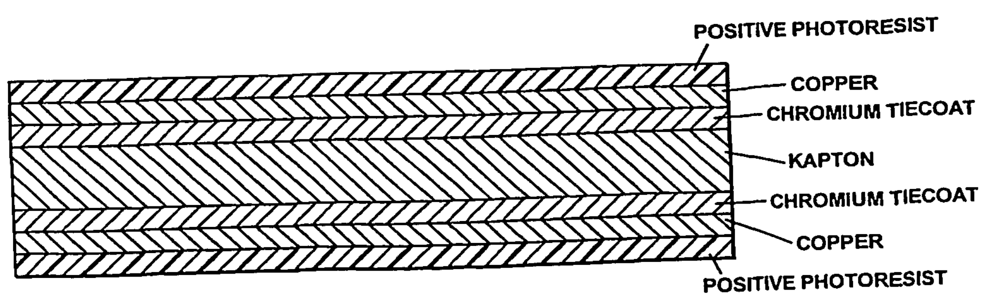


Fig. 14a

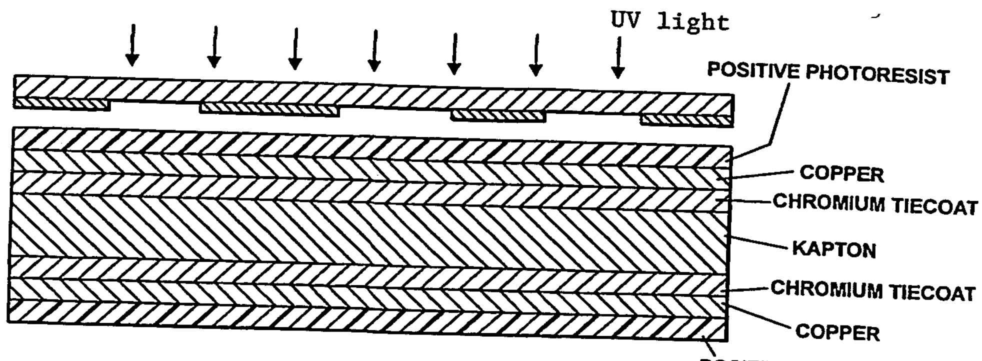


Fig. 14b

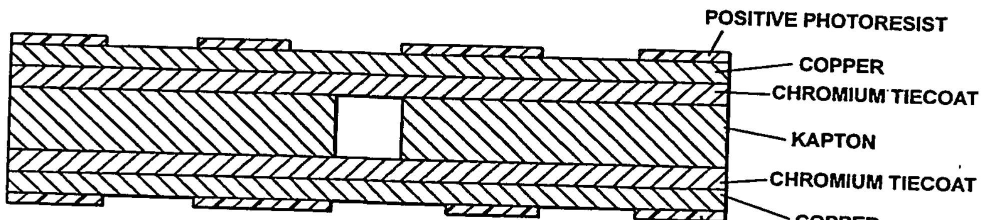


Fig. 14c

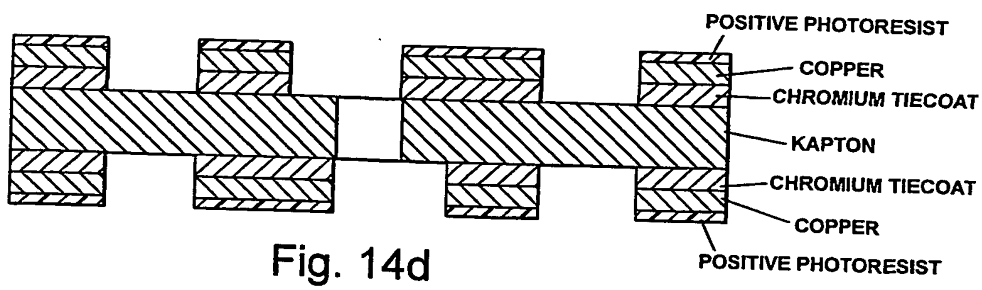


Fig. 14d

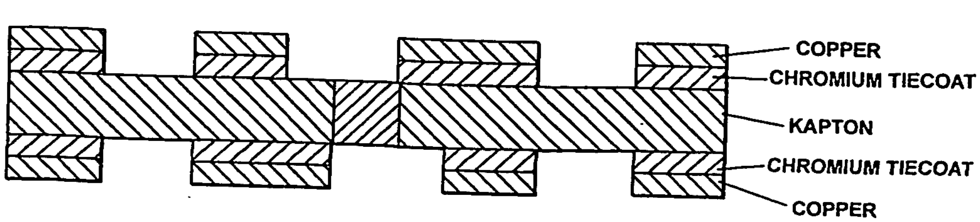


Fig. 14e

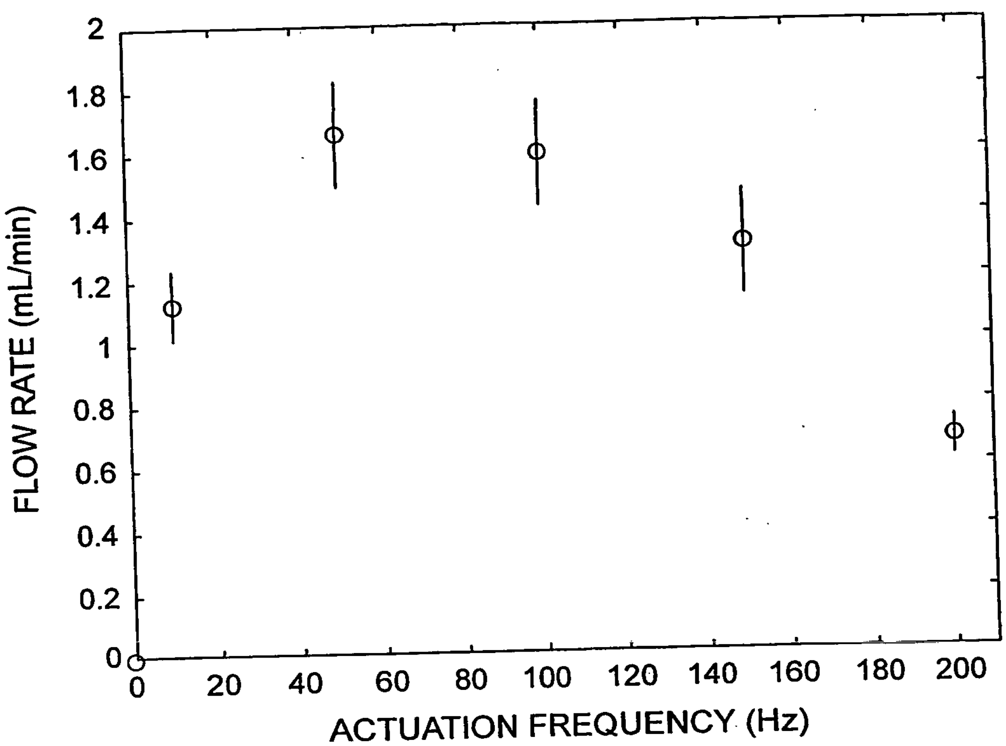


Fig. 15

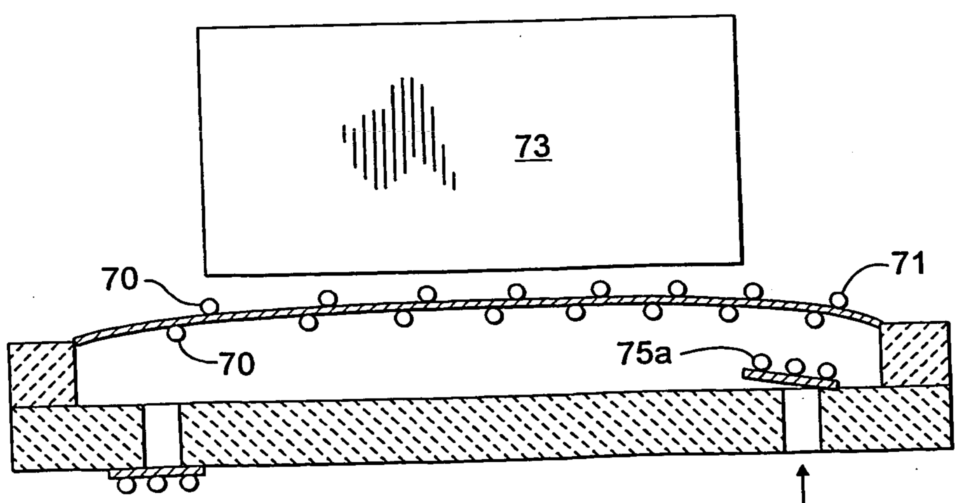


Fig. 16a

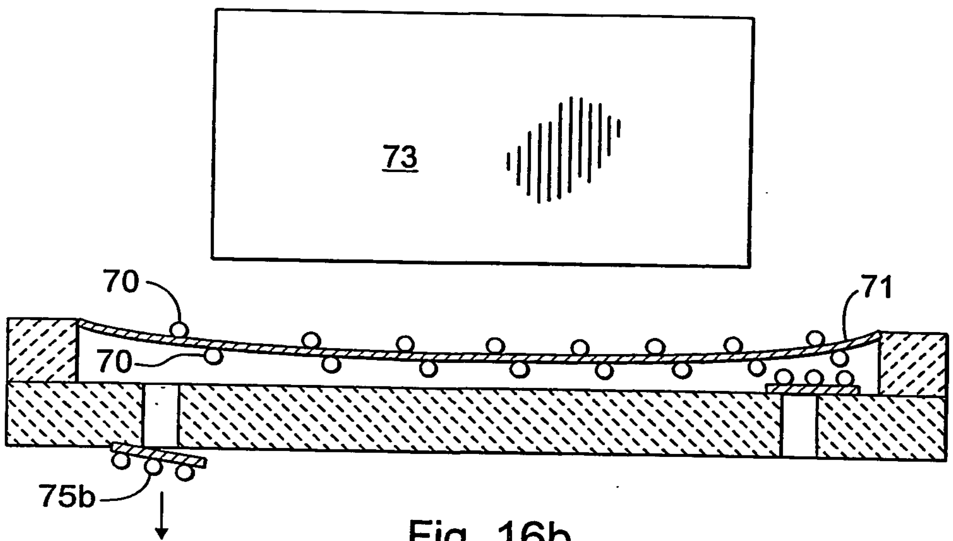


Fig. 16b

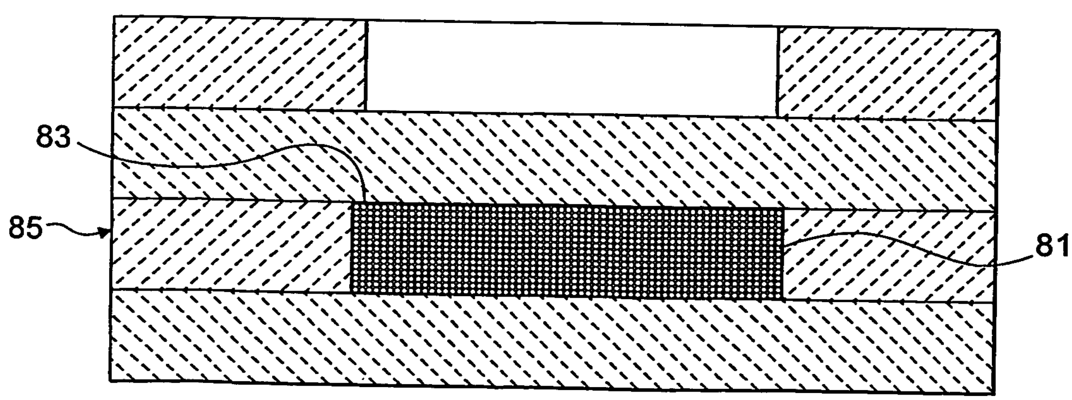


Fig. 17

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US00/30441

A. CLASSIFICATION OF SUBJECT MATTER

IPC(7) : H01P 1/10; H01H 51/22
US CL : 335/4, 78-86, 124, 128; 333/262, 101
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
U.S. : 335/4, 78-86, 124, 128; 333/262, 101

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
NONE

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 5,889,452 A (VUILLEUMIER) 30 March 1999, 30.03.1999), see entire document.	1-21
Y	US 5,847,631 A (TAYLOR et al.) 08 December 1998 (08.12.1998), see entire document.	1-21
Y	US 5,652,559 A (SAIA et al.) 29 July 1997 (29.07.1997), see entire document.	1-21
Y	US 5,467,068 A (FIELD et al.) 14 November 1995 (14.11.95), see entire document.	1-21

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

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Date of the actual completion of the international search 31 January 2001 (31.01.2001)	Date of mailing of the international search report 04 APR 2001
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703)305-3230	Authorized officer Michael Gellner Telephone No. (703)308-0956

Form PCT/ISA/210 (second sheet) (July 1998)